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Research article

Improved efficiency of soil solarization for growth and yield of greenhouse tomatoes

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Abstract – Soil solarization is a pre-planting treatment not based on chemicals, used in hot climates to control weeds and soil-borne pathogens. Its effectiveness has been widely demonstrated, for example, in the USA, Spain, Portugal, Egypt, Italy, Mexico, India and Iraq. However, an improvement in efficacy is needed before it can be widely adapted as a commercial practice. Supplementation of the soil with organic matter prior to solarization has been proposed as a management option, but its effectiveness has yet to be confirmed by any systematic study. Therefore, here we carried out a set of experiments in southern Italy over two seasons to study the effect of four levels of organic supplementation of 0, 0.35, 0.70 and 1.05 kg m^{-2} prior to solarization. Soil temperature and its chemical properties, as well as plant vegetation growth and fruit production were monitored for tomato plants grown under commercial greenhouse conditions. Organic supplementation increased the maximum soil temperature achieved through solarization by 3.9 °C to 4.7 °C. At 5 cm below the soil surface, a temperature of over 52 °C prevailed for 22 to 23 days when 0.70 kg m^{-2} organic supplement was incorporated, and for 14 to 13 days in the presence of 0.35 kg m^{-2} supplement, but this temperature was attained only for one day in the absence of any supplement. Organic supplementation significantly increased the soil concentration of NO_3^-–N, exchangeable K_2O, Ca^{2+} and Mg^{2+} and electrical conductivity. Increased available P_2O_5 and total N at the end of the crop cycle were also associated with supplementation of solarized soil. Plant vegetative growth was improved by supplementation, with crop plant stem diameter enhanced by up to 18%, above-ground vegetative fresh and dry weight by up to, respectively, 53 and 44%, and the number of leaves per plant by up to 16%. As the supplementation rate was raised from 0 to 0.70 kg m^{-2}, fruit yield was increased by about 70% (from 4.9 to 8.3 kg $plant^{-1}$). Organic matter supplementation may provide the basis for a more favorable sink/source balance for tomato cropping. We conclude that organic supplementation represents a beneficial management measure to increase the effectiveness of soil solarization, and that these results provide encouragement for the future commercial application of this environmentally-friendly technique.

soil solarization / organic supplementation / soil properties / tomato / plant growth / fruit yield

1. INTRODUCTION

Fumigation with methyl bromide is heavily used as a means of reducing the incidence of weeds, soil-borne bacteria, fungi and nematodes. However, this chemical is well understood to be hazardous both to human and animal health, as well as being detrimental to the level of atmospheric ozone (Noling and Becker, 1994). As a result, under the revised Montreal Amendment (1997), its use since 2005 has only been allowed under certain defined "critical" conditions. There is a continuing and urgent need to identify alternative means for the control of soil-borne crop diseases. Chemical disinfection of the soil eradicates both beneficial and harmful biota, creating a vacuum, which is typically filled by pathogens (Gamliel et al., 2000). As a result, the situation after treatment can become worse than that which prevailed before. Thus, non-chemical control, and in particular the use of methods which are non-injurious to the health of humans, domestic animals and the soil flora are clearly desirable (Gamliel and Stapleton, 1997).

Soil solarization represents a non-chemical, pre-planting method for controlling soil-borne diseases and pests. It consists of covering a wet soil with a transparent polyethylene sheet during the hot season, so that the soil becomes sufficiently heated to destroy invertebrate pests, weed seed and microbes (Katan et al., 1987). Compared to other methods, it has a number of advantages, since it does not create a biological vacuum, stimulates root growth, and increases crop yield (Chen et al., 1991; Gamliel et al., 2000). Although the

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principle of solarization is simple, its mode of action is complex, because it involves not only the destruction of propagules, but also generates shifts in microbial populations and activity, and changes the physical and chemical properties of the soil. The change mainly depends on increasing soil temperatures reached during solarization (Le Bihan et al., 1997; Mauromicale et al., 2005a), as a consequence of the greenhouse effect created but, also partially, due to the elimination of evaporation (Mahrer, 1979). Technical improvements in the efficacy of solarization could enable its use to be extended beyond its current limits. One possible avenue could be to incorporate more organic matter into the soil, prior to covering with the plastic sheet (Gamliel and Stapleton, 1997; Bacha et al., 2007; Piedra-Buena et al., 2007). This approach, named biofumigation (Katan, 2000), has received a great deal of attention in recent years (Gamliel et al., 2000; Ozores-Hampton et al., 2005).

Both temperature and soil moisture influence the rate of mineralization of soil organic matter, and this process can be promoted by solarization. Over the short term at least, the concentration of some soil mineral nutrients is increased in hot soils (Akhtar and Malik, 2000; Thurìes et al., 2000; Gelsomino et al., 2006), thus potentially enhancing plant growth (Chen et al., 2000). Long-term use of solarization and high doses of organic supplementation to solarized soil can, however, also have negative effects on both plant growth and beneficial soil biota populations (Assaf et al., 2006). Plant growth can be reduced when a crop is planted before the organic material has been fully degraded (Gamliel et al., 2000). Since both increases and decreases in the availability of plant nutrients have been attributed to soil solarization (Grünzweig et al., 1999; Thuriés et al., 2000), a definitive explanation of these mechanisms remains to be formulated. At present, only a modest research effort has been devoted to researching the effect of supplementation dosage, and no systematic study of crop growth and production in supplemented solarized soils has yet been reported. Such additional information is needed to improve the performance of soil solarization, and hence encourage its adoption in commercial practice. Thus, our objectives were to evaluate the effectiveness of organic supplementation before solarization on (i) the soil temperature during the mulching; (ii) the chemical properties of the soil; (iii) the growth and development of tomato; and (iv) its yield and yield components. The choice of tomato as the test crop was driven by its predominance as a field and greenhouse horticultural crop in the coastal areas of the Mediterranean basin (Tognoni and Serra, 2003).

2. MATERIALS AND METHODS

2.1. Site, climate and soil

Greenhouse experiments were conducted during the 2003–2004 and 2004–2005 seasons on the coastal plain south of Siracusa (Sicily), southern Italy [37° 03′ N, 15° 18′ E, 10 m asl] in a moderately deep Calcixerollic Xerochrepts soil (USDA Soil Taxonomy). The soil consisted of 15.5% clay, 29.1% silt and 55.4% sand. At the beginning of the trial, the soil pH was 7.6, the organic matter content 2.0%, the total nitrogen content 0.17%, the level of available P 100 mg kg^{-1} and the level of exchangeable K 580 mg kg^{-1}. The experimental field had been cultivated in a potato-lettuce-watermelon rotation for almost 15 years, and covered in plastic and used for tomato production for the last six years. The local climate is semi-arid/Mediterranean, with mild winters and hot, rainless summers. The mean 30-year maximum summer monthly temperatures are 29.6 °C (June), 32.5 °C (July), 31.6 °C (August) and 27.3 °C (September) (Servizio Idrografico, 1959–1998).

2.2. Experimental design, organic supplementation and soil solarization

In both seasons, the experiments were arranged in a randomized block design with four replications, using a plot size of 3 × 15 m. In the first season, three levels of organic supplementation were incorporated into the soil two days before solarization [0 (SsA_0, level 1), 0.35 ($SsA_{0.35}$, level 2) and 0.70 ($SsA_{0.70}$, level 3) kg m^{-2}]. In the second season, to obtain a better estimate of the effects of the organic supplementation rate on the vegetative growth and fruit yield of tomato, the higher rate of 1.05 kg m^{-2}($SsA_{1.05}$, level 4) was added. The commercially formulated product Organor® (SCAM s.r.l., Modena – Italy), which contains organic C (32.0%), humic C (10.0%), humic acid (17.2%) and C/N (6.4), was used for supplementation. Organor, a pelleted preparation of sterilized cattle manure, chicken manure and roasted leather, was uniformly applied over the soil surface, and incorporated into the top 20 cm of the soil using a rotovator. One day prior to solarization, both the supplemented and non-supplemented soils were irrigated to field capacity to take advantage of the greater effectiveness of solarization in moist soils. In both seasons, solarization was achieved by covering the bare soil with a 30-μm transparent polyethylene film (≥88% total visible transmittance and 20% IR absorption) from 10 July to 9 September 2003, and from 2 July to 17 September 2004. The sheets were stretched close to the soil surface and then anchored. At the end of the solarization period, the sheets were carefully removed, avoiding as much as possible any disturbance to the soil.

The greenhouse, with a steel tubular structure and lateral windows along the sides, was covered by EVA (ethylene vinyl acetate) film of 200 μm thickness and a total visible transmittance ≥86%. In both seasons, the covering of the greenhouse was done after soil solarization, as is usual in the area.

2.3. Plant material and management practices

Five-week-old tomato plants [cv. Ikram F_1 (Syngenta)] were planted on 7 October 2003 and 7 October 2004, using a within-row planting distance of 0.4 m, and an inter-row spacing of 1.15 m (overall planting density equivalent to

$2.17\ m^{-2}$). Lateral shoots were removed manually when required, and the resulting single stems were trained on wire. Drip irrigation was supplied when the accumulated daily evaporation reached 25 mm. Bumblebees were introduced into the greenhouse to encourage pollination. Fruit harvesting continued from 29 January to 13 May 2004 [114 days after planting (DAP) until 219 DAP], and from 2 February to 27 May 2005 (118 DAP-232 DAP).

2.4. Soil temperature measurement

During the solarization period, in both seasons, the soil temperature was recorded every 30 min, at 5 and 15 cm below the soil surface, using a number of thermistor sensors within a wire probe (HI 762W) buried in the center of the SsA_0, $SsA_{0.35}$ and $SsA_{0.70}$ plots, and connected to a portable digital HI 98840 microprocessor (Hanna Instruments, Padova, Italy).

2.5. Soil analysis

To aid in the interpretation of the first season's results, soil pH, electrical conductivity (EC) and total N, NO_3^-–N, exchangeable K_2O, available P_2O_5, K^+, Ca^{2+}, Mg^{2+} and Na^+ content were also measured the second season. For the SsA_0, $SsA_{0.35}$ and $SsA_{0.70}$ treatments, three soil samples per plot were collected with a 4-cm (i.d.) core auger to a depth of 5–15 cm, fractured into aggregates by hand pressure, air-dried and sieved (<2 mm). The first sampling date was in September 2004, two days after solarization was completed, and the second in June 2005, one day after the end of the cropping cycle. To minimize border effects of the solarization treatment, samples were taken from the middle of each plot. Samples destined for NO_3^-–N content analysis were stored in a refrigerated container before transport to the laboratory and analyzed the following day. Soil pH, EC, total N and available P_2O_5 were analyzed using widely employed methods, and adopted in Italy as the UNICHIM (1985). The analysis of NO_3^-–N and exchangeable K_2O was carried out following procedures described in *The Official Italian Methods of Soil Analysis* (Gazzetta Ufficiale, 1992). Ca^{2+}, Mg^{2+} and Na^+ analyses were obtained according to procedures approved by the Italian Society of Soil Science (SISS, 1985). Saturated paste was prepared by adding deionized water to approximately 200 g of soil sample as received until it reached a condition of complete saturation, as described by the guidelines of the Italian Society of Soil Science (SISS, 1985).

2.6. Tomato growth and fruit production

The diameter of the stem between the fourteenth and fifteenth leaves was measured non-destructively using a pair of calipers, and expressed as the mean of ten plants per replicate. Two measurements were made in each season – at 105 and 151 DAP in the first, and at 115 and 161 DAP in the second. The total numbers of leaves and fruit clusters per plant were recorded. Over the harvesting period, the number and weight of completely ripe fruits from ten plants per plot were noted. At the end of the growing period, the above-ground biomass of four plants per replicate was partitioned into stems and leaves, and respective dry weights were determined after their desiccation in a 65 °C oven until a steady weight was attained. Dry matter partitioning between plant organs (stem, leaf and fruit) was also monitored.

Table I. The effect of organic supplementation on soil temperature during solarization. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$) or 0.70 ($SsA_{0.70}$) kg m^{-2}, incorporated into the soil before solarization. The values represent the absolute and mean (in brackets) temperature maxima and minima during the solarization period (61 days in 2003 and 77 days in 2004) at two soil depths.

Treatment	5 cm		15 cm	
	T° max	T° min	T° max	T° min
	°C			
	2003			
SsA_0	51.9 (48.5)	27.8 (34.9)	45.1 (41.9)	28.3 (36.0)
$SsA_{0.35}$	53.8 (50.3)	29.2 (36.7)	47.1 (43.7)	29.7 (37.9)
$SsA_{0.70}$	56.6 (52.0)	30.5 (36.5)	49.4 (45.4)	29.4 (37.4)
	2004			
SsA_0	52.9 (49.4)	26.2 (31.8)	46.9 (44.9)	25.6 (32.6)
$SsA_{0.35}$	54.7 (51.2)	26.7 (33.5)	48.7 (46.8)	27.1 (34.5)
$SsA_{0.70}$	56.8 (53.1)	27.5 (32.9)	51.1 (48.4)	28.3 (34.8)

2.7. Statistical analysis

The data were subjected to analysis of variance (ANOVA) where appropriate, and means were compared by Fisher's protected least significant difference (LSD) test ($P \leq 0.05$). A polynomial (linear or quadratic) regression analysis was applied to define the relationship between supplementation treatment and various crop parameters. Fruit yield rate was estimated from the slope of the linear regression fitted between accumulation of ripe fruit fresh weight at each harvest and harvest date expressed in days. The significance of differences between regression coefficients was evaluated by a parallelism test (Ottaviano, 1977).

2.8. Temperature during the crop cycle

Over the period from October to early May, the mean temperature maxima and minima in the greenhouse were 33.3 °C and 18.8 °C, respectively, in the first season, and 31.6 °C and 18.0 °C in the second season.

3. RESULTS AND DISCUSSION

3.1. Soil temperature

In both seasons and at both depths, the incorporation of organic supplementation increased the soil temperature during solarization (Tab. I). In the $SsA_{0.70}$ treatment, a maximum

Table II. The effect of organic supplementation on the number of days during which the soil temperature exceeded 42 °C, 44 °C, 46 °C, 48 °C, 50 °C, 52 °C or 54 °C at two soil depths. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$) or 0.70 ($SsA_{0.70}$) kg m^{-2}, incorporated into the soil before solarization.

Treatment	5 cm							15 cm					
	≥42 °C	≥44 °C	≥46 °C	≥48 °C	≥50 °C	≥52 °C	≥54 °C	≥42 °C	≥44 °C	≥46 °C	≥48 °C	≥50 °C	≥52 °C
2003													
SsA_0	53	48	42	34	19	0	0	35	18	0	0	0	0
$SsA_{0.35}$	55	53	45	36	24	14	0	37	21	14	0	0	0
$SsA_{0.70}$	57	55	51	43	32	22	7	39	25	16	6	0	0
2004													
SsA_0	62	57	51	45	21	1	0	45	28	13	0	0	0
$SsA_{0.35}$	66	61	54	43	28	13	4	47	29	26	10	0	0
$SsA_{0.70}$	67	64	62	51	34	23	10	48	33	27	15	8	0

temperature of >56 °C at a depth of 5 cm was reached in both years. These levels were 2.8 °C (first season) and 2.1 °C (second season) higher than those achieved at the same depth in $SsA_{0.35}$, and 4.7 °C (first season) and 3.9 °C (second season) higher than in SsA_0. The outcome of the $SsA_{0.35}$ experiment was consistent with the effect of a 2–3 °C increase in the temperature of a solarized soil amended with chicken compost over that experienced in a solarized, non-supplemented soil (Gamliel and Stapleton, 1993).

The magnitude of this increase in maximum temperature was maintained, almost unaltered, at a depth of 15 cm in both years. The maximum soil temperature (both absolute and average) was consistently higher in $SsA_{0.70}$ than in $SsA_{0.35}$, which in turn was higher than in SsA_0 (Tab. I).

The number of days during which the maximum soil temperature equaled or exceeded 42, 44, 46, 48, 50, 52 and 54 °C at depths of 5 and 15 cm is shown in Table II. A temperature ≥52 °C at 5 cm was recorded for 22 (first season) and 23 (second season) days in $SsA_{0.70}$, for 14 and 13 days in $SsA_{0.35}$, and for 0 and 1 days in SsA_0 (Tab. II). This rise in temperature is probably sufficient to control many pathogenic organisms, and is likely to affect the activity, ecology and population dynamics of the whole soil biota (Stotzky, 1974; Gamliel et al., 2000; Gelsomino and Cacco, 2006). In addition, the elevated temperature encourages the breakdown of organic matter, with the consequent accumulation of volatile compounds damaging to many soil-borne pathogens and weed seeds, but which simultaneously stimulate the activity of antagonistic micro-organisms, and so provide a further layer of control over weeds, soil-borne plant pathogens and root nematodes (Oka et al., 2007). In the rhizosphere of lettuce plants grown in solarized soil supplemented with chicken manure compost, the representation of both *Bacillus* spp. and fluorescent Pseudomonads was increased (Gamliel and Stapleton, 1993), while more recently, DNA fingerprinting analyses have shown that solarization of supplemented soils has a marked effect on the population structure of the soil biota (Gelsomino and Cacco, 2006).

The diurnal fluctuation in soil temperature at 5 and 15 cm below the surface is illustrated in Figure 1, which shows how the differences between the supplementation treatments were most evident between 12.00 and 16.00 h.

3.2. Chemical properties of soil

We have shown here that organic supplementation prior to solarization results in an increase in both the availability of soluble nutrients (NO_3^-–N, K_2O, Ca^{2+}, Mg^{2+}) and the level of EC (Tab. III). The concentration of nutrients and the EC were both directly related to the extent to which the soil was heated, which, in turn, was governed by the supplementation rate at least up to 0.70 kg m^{-2}. Similar increases in soil nutrient concentration following soil solarization have been documented by Stapleton et al. (1985) and Mauromicale et al. (2005b). These increases occurred where soil temperature was increased, but not when wet, film-covered soil was insulated from solar heating (Stapleton et al., 1985), an observation which confirms that the increase in soil nutrient content is temperature-driven. Chen et al. (1991) have suggested that a soil which has been solarized over the summer may not maintain its level of NO_3^-–N over the winter. The present study shows similarly that in solarized, supplemented soils, the concentrations of NO_3^-–N, Ca^{2+}, Mg^{2+}, Na^+ and EC all decreased, by varying degrees, between the first and the second sampling date, whereas the total N content, exchangeable K_2O and available P_2O_5 increased. The highest increases were recorded in the $SsA_{0.70}$ plots (Tab. III). Overall, supplementation was beneficial for soil fertility, as it helped maintain the level of soil nutrients.

3.3. Vegetative plant growth

The improvement in the chemical and physical condition of the soil achieved by organic supplementation prior to solarization promotes plant growth. There appears to be a significant positive correlation between the growth response and supplementation rate. In both seasons, the stem diameter, vegetative fresh and dry weight and the number of leaves per plant

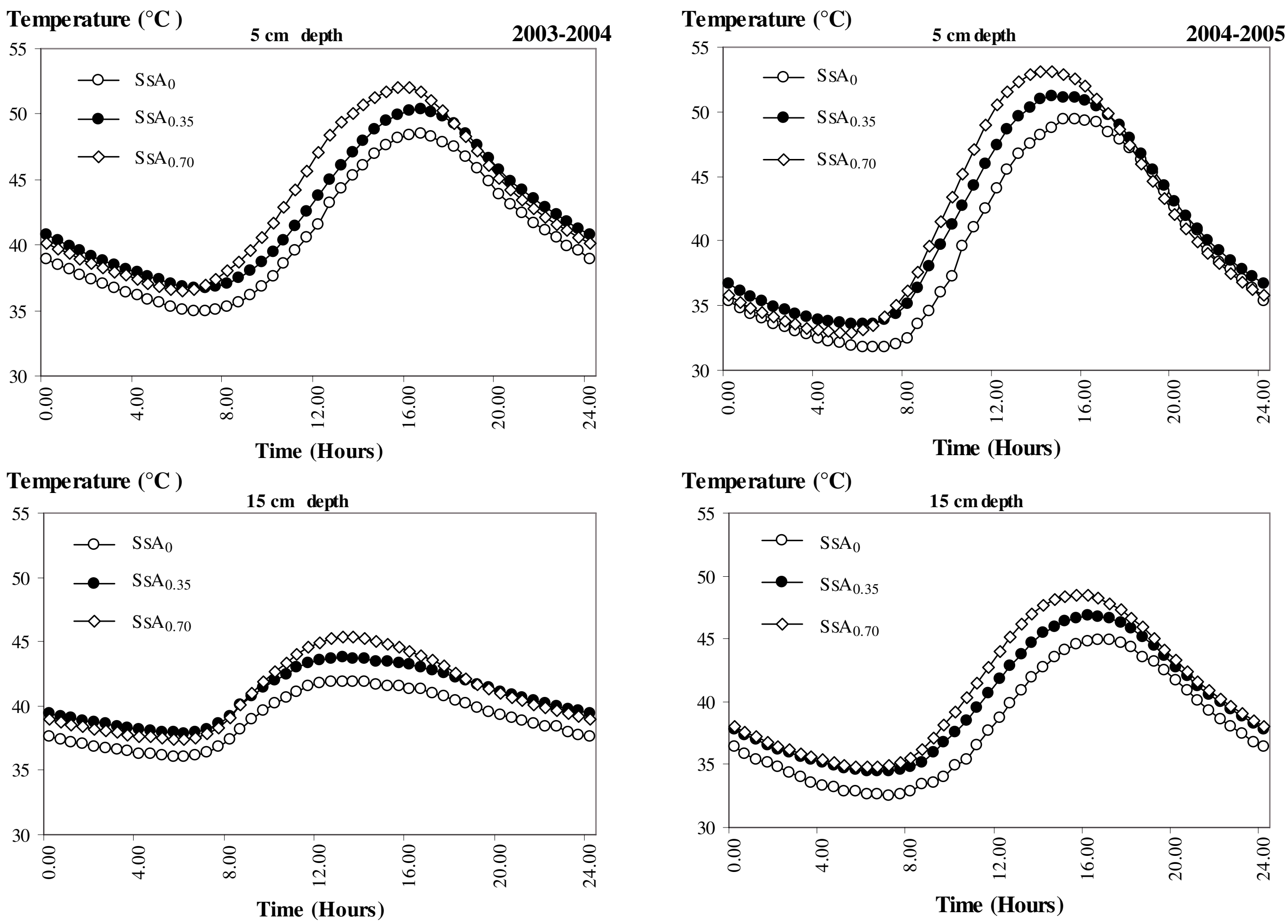

Figure 1. The effect of organic supplementation on diurnal trends in the soil temperature at two soil depths. Each symbol represents a half-hourly mean temperature over the entire period of soil solarization. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$) or 0.70 ($SsA_{0.70}$) kg m^{-2}, incorporated into the soil before solarization.

all increased linearly with supplementation rate (Tabs. IV, V). Vegetative fresh and dry weight increased by, respectively, 27% and 22% as the supplementation rate increased from 0 to 0.70 kg m^{-2} in the first season, and by 53% and 44% as it was increased from 0 to 1.05 kg m^{-2} in the second (Tab. V). The greater plant growth was balanced, in the sense that it led to a significant increase in both the number of fruit clusters per plant and the number of fruits per plant (Tabs. V, VI).

The dry matter percentage of stem + leaves, on the contrary, linearly decreased with the increase in amendment rate, in both seasons (Tab. V). No evidence of any phytotoxic effect of supplementation was observed in either season.

3.4. Fruit yield and its components

All fruit yield parameters increased linearly with the rate of supplementation (Tab. VI). As the rate increased from 0 to 0.70 kg m^{-2}, total fresh fruit yield increased by 69% (4.8 to 8.1 kg plant^{-1}) in the first season, and by 73% (4.9 to 8.5 kg plant^{-1}) in the second (Tab. VI). At the higher rate of 1.05 kg m^{-2}, however, fruit yield was only 88% of that achieved in $SsA_{0.70}$, resulting in the significance ($P \leq 0.05$) of the quadratic term in the regression (Tab. VI). It was clear that the most productive regime with respect to fruit yield ($SsA_{0.70}$) did not correspond with the one promoting the largest increase in plant growth ($SsA_{1.05}$). The positive effects of supplementation on fruit yield were due mostly to a higher number of fruits per plant, rather than to any increase in mean fruit weight (Tab. VI). Plants grown in supplemented soil produced 67.7 (first season) and 71.1 (second season) fruits per plant, with a mean fruit weight of, respectively, 113.5 and 112.3 g; in comparison, those grown in non-supplemented soil yielded only 49.6 and 52.3 fruits per plant, with a mean weight of 110.0 and 103.6 g (Tab. VI). The supplementation rate led to a significant increase in both the number of fruit clusters per plant and the mean number of fruits per cluster (Tabs. V, VI), positively balancing the greater plant growth.

Table III. The effect of organic supplementation on soil pH, electrical conductivity (EC) and element concentration in soil extracts during the 2004–2005 season. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$) or 0.70 ($SsA_{0.70}$) kg m^{-2}, incorporated into the soil before solarization.

Parameter		September 2004[1]			Significance	June 2005[2]			Significance
		SsA_0	$SsA_{0.35}$	$SsA_{0.70}$		SsA_0	$SsA_{0.35}$	$SsA_{0.70}$	
pH		7.51	7.59	7.63	NS	7.87	7.99	8.18	NS
K_2O (exchangeable)	mg kg^{-1}	563 c	622 b	668 a	**	721 c	780 b	900 a	**
P_2O_5 (available)	mg kg^{-1}	130	132	135	NS	155 b	167 b	221 a	*
$NO_3^- - N$	mg kg^{-1}	0.5 c	1.1 b	1.5 a	**	0.5 b	0.6 b	1.0 a	*
Total-N	‰	1.4	1.8	1.6	NS	1.8 b	2.3 ab	2.9 a	*
Saturated soil paste									
Ca	meq L^{-1}	32.6 c	54.2 b	73.4 a	***	14.8 c	17.7 b	21.2 a	**
Mg	meq L^{-1}	5.9 c	8.7 b	10.2 a	**	2.3 c	4.1 b	3.3 a	**
Na	meq L^{-1}	24.9 c	29.5 b	33.9 a	*	7.7 b	9.5 a	9.3 a	*
E C	dS m^{-1}	4.6 c	6.8 b	8.4 a	**	2.2 c	2.8 b	3.1 a	**
Exchangeable cations									
K	meq 100 g^{-1}	1.2 b	1.3 b	1.5 a	*	1.5 b	1.7 b	2.1 a	*
Ca	meq 100 g^{-1}	26.3 b	27.3 b	29.1 a	*	25.2	26.0	27.7	NS
Mg	meq 100 g^{-1}	3.2 c	3.5 b	3.6 a	**	3.2	3.3	3.3	NS
Na	meq 100 g^{-1}	1.8	2.8	2.4	NS	1.6	1.8	1.7	NS
C.S.C.		33.8 b	34.1 b	36.9 a	*	32.4	32.8	34.5	NS

[1] After solarization e before the tomato crop cycle.

[2] After the tomato crop cycle. Different letters within the same row show significant differences (LSD test, $P \leq 0.05$). *, **, ***, NS, significant difference at $P \leq 0.05$, 0.01, 0.001 and not significant, respectively.

Table IV. The effect of organic supplementation on stem diameter over two crop seasons. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$), 0.70 ($SsA_{0.70}$) or 1.05 ($SsA_{1.05}$) kg m^{-2}, incorporated into the soil before solarization.

Treatment	Stem diameter (mm)	
	2003–2004	
	105 DAP[1]	*151 DAP*
SsA_0	12.7 a	15.2 c
$SsA_{0.35}$	12.9 a	16.1 b
$SsA_{0.70}$	13.2 a	17.4 a
F	N.S.	***
L	**	**
	2004–2005	
	115 DAP	*161 DAP*
SsA_0	12.7 d	16.0 d
$SsA_{0.35}$	13.4 c	16.3 c
$SsA_{0.70}$	14.2 b	18.0 b
$SsA_{1.05}$	15.0 a	18.7 a
F	***	***
L	***	***

[1] DAP = Days after planting.

Different letters within the same row show significant differences (LSD test, $P \leq 0.05$). Significance levels for linear (L) regression term (quadratic and cubic was not significant). **, ***, NS, significant difference at $P \leq 0.01$, 0.001 and not significant, respectively. F, variance ratio.

Notably, the overall fruit yield levels of 177 t ha^{-1} in the first season and 184 t ha^{-1} in the second season were, respectively, 149% and 159% above the long-term average for greenhouse-grown tomatoes in Italy (ISTAT, 2006–2007).

The effect of organic supplementation was, therefore, more marked on the reproductive than on the vegetative phase of the crop. Thus it appears that solarized, supplemented soils provide the basis for a more favorable sink/source balance. The fruit dry weight/leaf dry weight ratio increased linearly with the supplementation rate. For $SsA_{0.70}$, this ratio was almost twice that for SsA_0. On the other hand, the $SsA_{1.05}$ treatment was less effective than $SsA_{0.70}$ (Tab. VI). In both seasons, the fruit yield rate was clearly improved by supplementation up to 0.70 kg m^{-2}. The slope of the regression relating fruit yield accumulation to harvest date increased significantly ($P \leq 0.01$) from 0.051 (SsA_0) to 0.059 ($SsA_{0.35}$) to 0.084 ($SsA_{0.70}$) in the first season, and from 0.046 (SsA_0) to 0.057 ($SsA_{0.35}$) to 0.081 ($SsA_{0.70}$) in the second season. However, the slope was reduced to 0.072 for $SsA_{1.05}$ (Fig. 2).

4. CONCLUSION

Under the Mediterranean conditions typical of southern Italy, the addition of organic supplementation before solarization has proven to be an excellent means of improving the chemical properties of the soil and, consequently, the plant growth and fruit yield of greenhouse-grown tomatoes.

We have shown that the improvement in the soil condition brought about by organic supplementation can also play a role in determining levels of photosynthesis and chlorophyll fluorescence as well as the efficiency of assimilate translocation from the leaves to the fruit (unpublished data). The fruit dry weight/leaf dry weight ratio was approximately doubled in the $SsA_{0.70}$ treatment as compared with SsA_0. The mechanism(s)

Table V. The effect of organic supplementation on stem and leaf fresh and dry weight, dry matter percentage, and the total numbers of leaves and fruit clusters during two seasons. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$), 0.70 ($SsA_{0.70}$) or 1.05 ($SsA_{1.05}$) kg m^{-2}, incorporated into the soil before solarization.

Treatment	Stem + leaf: Fresh weight (g plant^{-1})	Stem + leaf: Dry weight (g plant^{-1})	Stem + leaf: Dry matter (%)	Leaf (n plant^{-1})	Fruit cluster (n plant^{-1})
			2003–2004		
SsA_0	1100 b	163 b	14.8 a	31 b	9 c
$SsA_{0.35}$	1113 b	164 b	14.7 a	32 b	10 b
$SsA_{0.70}$	1393 a	199 a	14.3 b	35 a	12 a
F	***	***	*	**	***
L	**	**	**	**	**
			2004–2005		
SsA_0	1114 d	168 d	15.1 a	31 d	9 d
$SsA_{0.35}$	1288 c	192 c	14.9 a	32 c	10 c
$SsA_{0.70}$	1584 b	223 b	14.1 b	35 b	12 a
$SsA_{1.05}$	1709 a	242 a	14.2 b	36 a	11 b
F	***	***	*	***	***
L	***	***	**	***	***

Different letters within the same row show significant differences (LSD test, $P \leq 0.05$). Significance levels for linear (L) regression term (quadratic and cubic was not significant). *, **, ***, significant difference at $P \leq 0.05$, 0.01 and 0.001, respectively. F, variance ratio.

Table VI. The effect of organic supplementation on total fruit yield, the number of fruits per plant and per cluster, mean fruit weight and fruit dry weight/leaf dry weight over two seasons. The rate of supplementation was 0 (SsA_0), 0.35 ($SsA_{0.35}$), 0.70 ($SsA_{0.70}$) or 1.05 ($SsA_{1.05}$) kg m^{-2}, incorporated into the soil before solarization.

Treatment	Total fresh fruit yield (kg plant^{-1})	Total fruit (n plant^{-1})	Fruit average weight (g)	Fruit per cluster (n)	Fruit dry weight/Leaf dry weight
			2003–2004		
SsA_0	4.8 c	49.6 c	110.0 b	5.4 c	2.17 c
$SsA_{0.35}$	5.6 b	58.7 b	109.0 b	5.9 b	2.81 b
$SsA_{0.70}$	8.1 a	76.8 a	118.1 a	6.5 a	4.56 a
F	***	***	***	***	***
L	***	***	**	**	***
Q	N.S.	N.S.	N.S.	N.S.	N.S.
			2004–2005		
SsA_0	4.9 d	52.3 d	103.6 d	5.6 c	1.94
$SsA_{0.35}$	6.0 c	61.4 c	106.3 c	6.2 b	2.95
$SsA_{0.70}$	8.5 a	82.2 a	114.0 b	7.0 a	3.81
$SsA_{1.05}$	7.5 b	69.6 b	116.7 a	6.3 b	2.99
F	***	***	***	**	***
L	***	***	***	***	***
Q	*	*	N.S.	*	**

Different letters within the same row show significant differences (LSD test, $P \leq 0.05$). Significance levels for linear (L) regression or quadratic (Q) term. *, **, ***, NS, significant difference at $P \leq 0.05$, 0.01, 0.001 and not significant, respectively. F, variance ratio.

whereby such physiological changes are effected remain as yet unexplored.

In conclusion, we have shown that organic supplementation represents a management option which can be applied to improve the utility of soil solarization. Its adoption in commercial practice should be straightforward, and can be expected to be most beneficial in climatically marginal regions where the soil temperatures achieved by conventional solarization are not on their own high enough to provide an effective level of control of the soil biota. The strategy is fully compatible with organic production systems, and should be broadly applicable to the highly intensive agro-ecosystems characteristic of greenhouse-grown horticultural crops. An additional benefit stems from the possibility of reducing both the application rate of mineral fertilizers, and the duration of the solarization treatment.

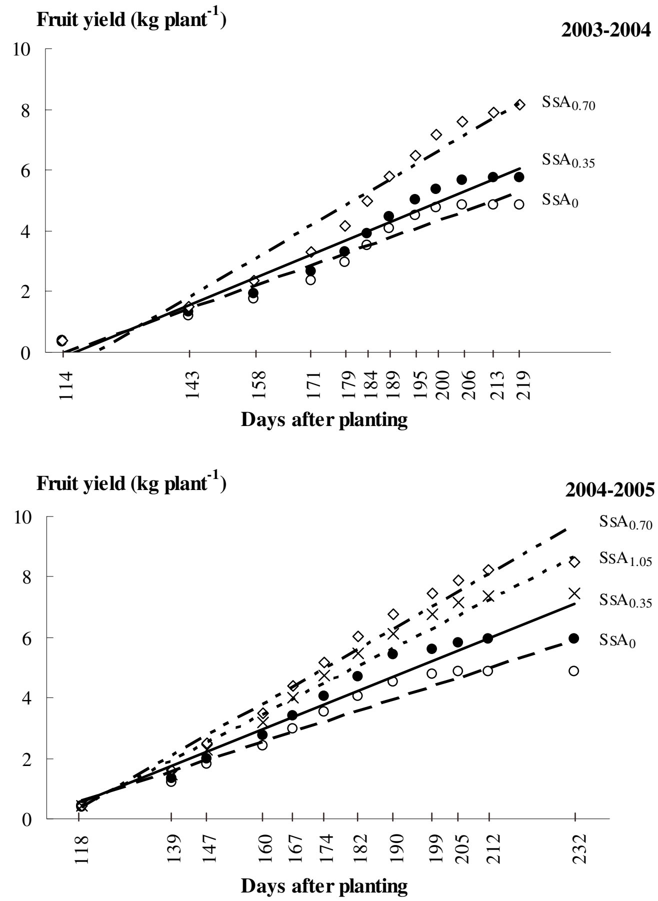

Figure 2. The relationship between fruit fresh weight and days after planting for three (2003–2004 season) and four (2004–2005 season) organic supplementation rates: 0 (SsA_0), 0.35 ($SsA_{0.35}$), 0.70 ($SsA_{0.70}$) and 1.05 ($SsA_{1.05}$) kg m^{-2}. Fruits were harvested at the red-ripe stage. Regression equations were: 2003–2004 (SsA_0: $y = 0.051x - 5.82$, $R^2 = 0.948$; $SsA_{0.35}$: $y = 0.059x - 6.96$, $R^2 = 0.956$; $SsA_{0.70}$: $y = 0.081x - 10.22$, $R^2 = 0.953$), 2004–2005 (SsA_0: $y = 0.046x - 4.85$, $R^2 = 0.922$; $SsA_{0.35}$: $y = 0.057x - 6.18$, $R^2 = 0.937$; $SsA_{0.70}$: $y = 0.081x - 9.24$, $R^2 = 0.966$; $SsA_{1.05}$: $y = 0.072x - 8.09$, $R^2 = 0.957$).

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