SOIL SOLARIZATION FOR WEED CONTROL IN CARROT[1]

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ABSTRACT - Soil solarization is a technique used for weed and plant disease control in regions with high levels of solar radiation. The effect of solarization (0, 3, 6, and 9 weeks) upon weed populations, carrot (*Daucus carota* L. cv. Brasília) yield and nematode infestation in carrot roots was studied in São Luís (2°35' S; 44°10' W), MA, Brazil, using transparent polyethylene films (100 and 150 µm of thickness). The maximum temperature at 5 cm of depth was about 10°C warmer in solarized soil than in control plots. In the study 20 weed types were recorded. Solarization reduced weed biomass and density in about 50% of weed species, including *Cyperus* spp., *Chamaecrista nictans* var. *paraguariensis* (Chod & Hassl.) Irwin & Barneby, *Marsypianthes chamaedrys* (Vahl) O. Kuntze, *Mitracarpus* sp., *Mollugo verticillata* L., *Sebastiania corniculata* M. Arg., and *Spigelia anthelmia* L. Approximately 40% of species in the weed flora were not affected by soil mulching. Furthermore, seed germination of *Commelina benghalensis* L. was increased by soil solarization. Marketable yield of carrots was greater in solarized soil than in the unsolarized one. It was concluded that solarization for nine weeks increases carrot yield and is effective for controlling more than half of the weed species recorded. Mulching was not effective for controlling root-knot nematodes in carrot.

Index terms: *Commelina benghalensis*, *Cyperus*, organic farming, soil heating, mulching, plastic film covers, soil desinfection, nematode controls, sandy soil.

SOLARIZAÇÃO DO SOLO PARA O CONTROLE DE PLANTAS DANINHAS NA CULTURA DE CENOURA

RESUMO - A solarização é uma técnica usada para o controle de plantas daninhas e doenças de plantas em regiões de alta radiação solar. Estudou-se o efeito da solarização (por 0, 3, 6 e 9 semanas) sobre a população de plantas daninhas, a produção de cenoura (*Daucus carota* L. cv. Brasília) e a infestação das raízes por nematóides. O experimento foi realizado em São Luís, MA, utilizando filmes de plástico com espessuras de 100 e 150 µm. A temperatura máxima a 5 cm de profundidade foi cerca de 10°C maior nas parcelas solarizadas do que nas testemunhas. Havia 20 tipos de ervas daninhas no experimento. A solarização reduziu a biomassa e densidade das plantas daninhas em 50% das espécies, incluindo *Cyperus* spp., *Chamaecrista nictans* var. *paraguariensis* (Chod & Hassl.) Irwin & Barneby, *Marsypianthes chamaedrys* (Vahl) O. Kuntze, *Mitracarpus* sp., *Mollugo verticillata* L., *Sebastiania corniculata* M. Arg. e *Spigelia anthelmia* L. No entanto, foi ineficaz para o controle de 40% das espécies vegetais presentes no campo. Além disso, a solarização estimulou a germinação das sementes de *Commelina benghalensis* L. O rendimento comercial da cenoura foi maior nas parcelas solarizadas do que naquelas não cobertas. Conclui-se que a solarização por nove semanas aumenta o rendimento da cenoura e foi eficiente para o controle de mais da metade das espécies de plantas daninhas no campo. Porém, a cobertura de plástico foi ineficiente para o controle de nematóides formadores de galhas na cenoura.

Termos para indexação: *Commelina benghalensis*, *Cyperus*, agricultura orgânica, aquecimento do solo, cobertura do solo, cobertura de plástico, desinfecção do solo, controle de nematóides, solo arenoso.

INTRODUCTION

Weed management in carrot relies mainly on the use of herbicides in conventional agriculture. This is because it is seeded directly in narrow rows, which makes tillage unrecommended because of the injury it causes to roots, and on account of increasing cost or uncertainty in labor supply that makes timely

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handweeding control uneconomical or inefficient. Even though the introduction of selective herbicides has had one of the greatest effects on yield improvements, herbicide resistance of weeds and other potential side effects have raised concern about the intensive use of herbicides in cropping systems. Consistent with the current search for non-hazardous methods for controlling weeds is the application of integrated weed management strategies, which takes into account the need to increase agricultural production and to determine economic losses, risks to human health, energy and environmental factors, and potential damage to non-target organisms (Shaw, 1982).

Soil solarization is a special mulching technique in which moist soil is covered by polyethylene (PE) film and heated by solar radiation for several weeks. It is used for soil thermic disinfestation, being accomplished by mulching the soil under a plastic film, which produces a greenhouse effect, so that soil temperature rises to levels which are lethal or injurious to many soilborne organisms, including pathogens, seeds, and weed seedlings.

Soil solarization is also an effective and safe practice, which could be an important component of the overall weed management strategy in several crops. It was developed for control of soil pathogens by mulching the soil during the hot season (Katan et al., 1976). Its effects are greater in moist or wet soils; thus its success depends on moisture for maximum heat transfer to soilborne microorganisms and weed seeds. According to Elmore (1991), one of the primary purposes of solarization is to control weeds that are not susceptible to selective herbicides in a crop, such as *Malva parviflora* L., *Convolvulus arvensis* L., and *Abutilon theophrasti* Medik.

Transparent polyethylene films are recommended for soil solarization because of its high transmittance of short wave (0.3 - 3 μm) radiation, and its low transmittance of long wave (4 - 40 μm) radiation.

Winter annual weeds, e.g. *Lactuca serriola* L., *Poa annua* L., and *Senecio vulgaris* L., that germinate during cool temperatures have been effectively controlled by PE mulching, whereas some weeds that germinate during warmer periods have been reported to be tolerant, and a few, such as *Melilotus sulcatus* Desf. appear to be resistant to solarization (Elmore, 1991). Even though it is believed that solarization appears to be effective in reducing weed population (Egley, 1983; Al-Masoon et al., 1993; Vizantinopoulos & Katranis, 1993), soil tarping was ineffective for controlling *Indigofera* sp. (Marenco & Lustosa, 1997), and emergence of *Cyperus rotundus* L. from tubers was increased by polyethylene mulching (Kumar et al., 1993).

The decline in the viability of soilborne microorganisms and weed seeds during solarization depends on the soil temperature and exposure time. The direct effect of high temperature on susceptible organisms may be related to changes in the metabolism and ultrastructure of cells (Singla et al., 1997). However, some indirect effects, e.g. changes in concentrations of available nutrients (Stapleton et al., 1985) may also contribute to soil solarization effects.

The objective of this study was to evaluate the effect of solarization upon weed populations, carrot yield, and nematode infestation in carrot roots.

MATERIAL AND METHODS

The experiment was carried out at the experimental station of the Universidade Estadual of Maranhão, in São Luís, MA, Northeastern Brazil (latitude 2º35' S; longitude 44º10' W), from September 1996 to May 1997. The soil type in the experimental area was a Red-Yellow Podsol (Oxisol) with sandy texture (250 g kg^{-1} of coarse sand, 550 g kg^{-1} of fine sand, 100 g kg^{-1} of silt, and 100 g kg^{-1} of clay). Soil analysis made at the beginning of the study indicated a low natural fertility with pH of 5.0, 30 g kg^{-1} of organic matter, 7 mg dm^{-3} of P, and 0.9, 15 and 15 mmol$_c$ kg^{-1} of K, Ca and Mg, respectively. Total rainfall during the wet season, December to July, was 2,100 mm. During the study, mean air temperature was 26.1ºC, and the solar radiation (mean±SE), determined with a pyranometer (PY 23150 and LI-1000 datalogger, Licor, Nebraska, USA) was 16.78±0.52 MJ m^{-2} d^{-1}.

Four weeks before the beginning of mulching, the soil was disked three times and amended with 100 g m^{-2} of lime, and beds 1 m wide and 5 m long were made. The soil was irrigated up to field capacity to about a depth of 60 cm before mulching with transparent PE films (100 and 150 μm thickness). For solarization treatments (three, six, and nine weeks), plastic films were laid on the smoothed beds, stretched close to the soil surface, and their edges and ends were buried in trenches 10 cm deep and covered with soil. An unsolarized control treatment was also included. All beds including those for the uncovered treatment were constructed at the same time. At the end of the period of solarization, the films were removed without soil disturbance. For temperature measurements, from11:00 am up to 6:00 pm at random days, mercury thermometers were inserted into the soil to a depth of 5 cm at the beginning of the experiment and variation in temperature measured at one-hour intervals. Soil temperature was measured at 5 cm depth because the germination of weed seeds is concentrated in the upper layers of soil. In covered plots, thermometers were pushed through the plastic, and the hole was sealed with epoxy glue. Air temperature was recorded at 50 cm above the soil surface. Solarization treatments were initiated at different times, in such a way that mulching periods ended on the same day, then the crop was seeded. Just before planting, the soil was fertilized with NPK, at a rate of (g m^{-2}): 2.4 of N, as urea; 17.0 of P, as P_2O_5; 19.7 of K, as KCl. All nutrients were uniformly applied at 5 cm depth along the rows with a minimum disturbance of soil surface. Carrots were planted in January 1997, in rows spaced 20 cm apart at a density of 60 to 70 seeds per meter. After emergence, excess of seedlings were thinned to about 30 plants per meter. At the end of the plant cycle, about 120 days after planting (DAP), the plants were harvested and the roots examined for root-knot caused by nematode infestation. Thereafter, the fresh weight of roots was determined. Herbicides were not used during the experiment.

During the crop season, weed biomass and density were assessed in three 0.15 x 0.15 m randomly collected samples, at 15, 30 and 45 days after the films had been removed, except at 45 DAP when 1.5 x 0.2 m samples were collected. At each sampling time, weeds were severed at the soil surface, identified and separated into species groups. Shoots of weeds were oven-dried at 72ºC until reaching constant mass (about 72 hours), and weighed. The weeds were manually removed from plots after the last sampling was carried out. The design used in the experiment was a randomized complete block with four replications, and treatments in a split-plot arrangement. The main plots were the film thickness (100 and 150 µm), and the subplots was the duration of solarization. In order to easily compare the effect of solarization on weed species, dry mater and density data were transformed to relative values (Y_r) as follows:

$Y_r = (Y_{ij}/Y_{ij\text{-}max}) \times 100$

where Y_{ij} represented the i observed value of the j treatment and $Y_{ij\text{-}max}$ corresponded to the greatest i observed value of the j treatment. To homogenize variance, data derived from weighing and counting were transformed to log(Y+1) and $(Y+0.5)^{0.5}$, respectively (Steel & Torrie, 1981) before conducting statistical analysis.

RESULTS AND DISCUSSION

Maximal soil temperature at a depth of 5 cm reached nearly 52ºC under polyethylene film covered plots, whereas it was only 42ºC in the uncovered plots (Table 1). Solarization reduced total dry matter accumulation and density of weeds at 15, 30 and 45 days after the PE films had been removed, i.e., at 15, 30 and 45 DAP of carrots (Table 2). However, there was no difference ($P>0.05$) between PE thickness. In the first sampling (15 DAP), the reduced growth of weeds made it difficult to evaluate the effect of solarization on individual weed species, therefore, only data for the sum of weeds were obtained. Weed DM accumulation was reduced from 11.9 g m^{-2} in control plots to 0.89 g m^{-2} in those solarized for nine weeks, indicating the effectiveness of PE mulching on weed control. The factors involved in solarization has been attributed to soil temperature, moisture, and probably gases (Horowitz et al., 1983). High temperatures may cause damaging changes in enzyme activity, membrane structure, and protein metabolism (Singla et al., 1997). On the other hand, a high concentration of CO_2 in the soil atmosphere, which has been observed during solarization (Horowitz et al., 1983), can induce seed dormancy (Mayer & Poljakoff-Mayber, 1989). As a result, soil solarization reduces the number of weed seedlings and weed biomass of heat-sensitive species.

In the study, 20 weed types were recorded. All of these were single species, but *Cyperus* represented a congeneric grouping that included at least two species. A group of six infrequent weed types were difficult to identify, and the group was classified as unidentified weeds.

At 30 DAP, soil tarping reduced dry matter accumulation and density in several weed species. In decreasing order, the effect was greater in *Chamaecrista nictans* (Chod & Hassl.) Irwin & Barneby, *Marsypianthes chamaedrys* (Vahl) O. Kuntze, *Cyperus* spp., *Mollugo verticillata* L., *Sebastiania corniculata* W. Arg., *Spigelia anthelmia* L., and

Mitracarpus sp. (Fig. 1). There was no effect of solarization on populations of *Panicum hirtum* Lam., *Croton lobatus* L., *Indigofera hirsuta* L., *Phyllanthus amarus* Schum, and *Eragrostis ciliaris* (L.) R. Br. Even though solarization has been considered to be effective for controlling weeds, especially annual weeds, the population of *C. benghalensis* was increased by solarization. A quadratic relationship was observed between its growth and the duration of mulching (Fig. 1). The effect of solarization on dry matter accumulation and density of the perennial *Cyperus* spp. confirms previous reports (Kuva et al., 1995). Under tropical conditions, Kumar et al. (1993) also observed that solarization may reduce population of *C. rotundus* when emerged from seeds, but not when their flushes had been emerged from tubers. By differentiating equations fitted for both dry matter accumulation and plant density of *C. benghalensis* with respect to time, it was estimated that the stimulatory effect of solarization on this weed was greater at 37 days of PE mulching. Therefore, this indicates that a few weeks of solarization induces the germination of *C. benghalensis* dormant seeds, and that periods of mulching longer than six weeks may either reduce the viability of seeds or induce secondary seed dormancy. Thus, it may be suggested that the whole process acting on breaking of dormancy of *C. benghalensis* seeds shows greater activity when they are exposed to a relative narrow period of favorable high temperature, a process which could be referred to as stratification at high temperature. It has been reported (Egley, 1990) that germi-

TABLE 1. Air temperatures (ºC) at 50 cm aboveground and soil temperatures (ºC) at 5 cm depth recorded at the hottest time of day in solarized and non-solarized plots (mean ± SE, n = 15).

Time of day	Air temperature	Non-solarized plots	Solarized plots (plastic thickness)	
			100 µm	150 µm
11:00 am	36.4 ± 0.5	36.8 ± 0.3	40.8 ± 0.4	41.5 ± 0.4
12:00 pm	37.8 ± 0.4	41.0 ± 0.3	45.2 ± 0.4	45.8 ± 0.4
1:00 pm	40.3 ± 0.4	41.7 ± 0.4	48.0 ± 0.3	49.5 ± 0.3
2:00 pm	38.3 ± 0.5	42.0 ± 0.4	49.5 ± 0.3	51.8 ± 0.3
3:00 pm	36.5 ± 0.4	42.0 ± 0.4	48.7 ± 0.3	51.0 ± 0.3
4:00 pm	35.0 ± 0.5	41.7 ± 0.5	47.3 ± 0.4	49.5 ± 0.4
5:00 pm	32.0 ± 0.4	40.0 ± 0.4	44.0 ± 0.3	48.5 ± 0.4
6:00 pm	29.0 ± 0.5	37.8 ± 0.5	41.2 ± 0.4	44.5 ± 0.3

TABLE 2. Total weed dry matter accumulation and weed density at 15, 30 and 45 days after the films had been removed.

Solarization time (weeks)	15 days after film removal		30 days after film removal		45 days after film removal	
	Weed DM accumulation (g m^{-2})	Weed density (nº m^{-2})	Weed DM accumulation (g m^{-2})	Weed density (nº m^{-2})	Weed DM accumulation (g m^{-2})	Weed density (nº m^{-2})
0	11.90	1650.00	137.85	2449.99	316.44	1057.08
3	4.79	951.85	85.96	1685.18	245.67	861.67
6	2.07	570.37	54.89	1149.99	195.30	553.75
9	0.89	227.77	29.44	525.92	127.00	314.17
F test	*	*	*	*	*	*

* Significant at P = 0.05.

nation of some seeds may be enhanced when soil temperatures reach 50 to 60ºC, as dormancy imposed by coats is broken.

At 45 DAP, the effect of solarization upon *M. verticillata*, *S. anthelmia*, *C. benghalensis*, *Cyperus* sp. and *Mitracarpus* sp. was similar to that observed at 30 days after film removal (Fig. 2). Nevertheless, *C. nictans*, *M. chamaedrys*, and *S. corniculata* were no more affected by PE mulching. This suggests that the mulching effect observed at 30 DAP was due to secondary seed dormancy induced by soil tarping, which was lost some weeks later after film removal. On the other hand, there was a non-significant (P>0.05) trend towards an enhanced effect of mulching on DM accumulation of *I. hirsuta*, which is likely due to breaking of seed dormancy by high soil temperature. In *Acacia kempeana* (Mueller), the strophiole lifts and cracks in response to heat, so that water enters into the seed and germination become possible (Hanna, 1984). In this study, seedling emergence was enhanced by solarization in *C. benghalensis*, i.e., about one in 20 species, which represents 5% of the weed flora.

Taking into account population density and biomass production of the weed community, the most important weeds were *Cyperus* spp., *Mitracarpus* sp., and *C. benghalensis.* Since there was no difference in these parameters between plants collected at 30 or 45 DAP, just relevant data for the last sampling are presented for these weeds (Fig. 3). It is noteworthy that the contribution of *C. benghalensis* to the total biomass of the weed community increased from less than 3% in control plots to about 35% in those solarized for nine weeks. On the other hand, its density

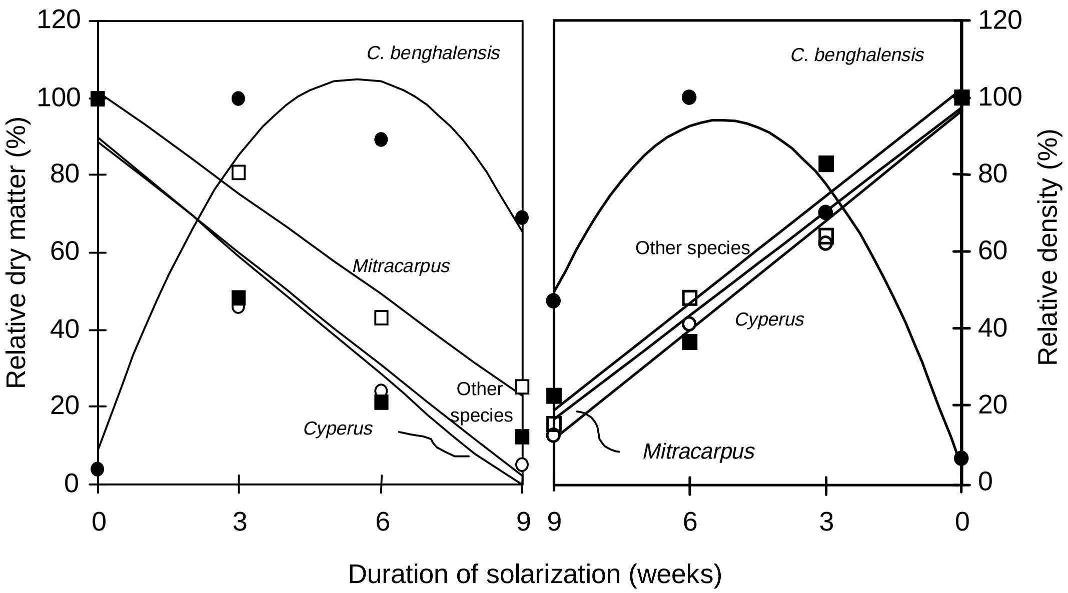

FIG. 1. Relative weed dry matter and relative density at 30 days after film removal. Relative weed dry matter: *Cyperus* spp. (-O-), y_r = 89.80 – 10.23t, R^2 = 0.92; *C. benghalensis* (-●-), y_r = 8.90 + 35.13t – 3.2t^2, R^2 = 0.91; *Mitracarpus* sp. (- -), y_r = 101.70 – 8.77t, R^2 = 0.98; other species, (-■-), y_r = 88.82 - 9.64t; R^2 = 0.90; relative density: *Cyperus* spp. (-O-), y_r = 96.50 – 9.50t, R^2 = 0.99; *C. benghalensis* (-●-), y_r = 3.55 + 34.35t – 3.27t^2, R^2 = 0.97; *Mitracarpus* sp. (- -), y_r = 97.40 – 9.03t, R^2 = 0.98; other species (-■-), y_r = 102.25 – 9.3t, R^2 = 0.95. Where t is the duration of solarization (weeks). The group classified as other species included: *C. nictans* var. *paraguariensis*, *M. chamaedrys, M. verticillata, S. corniculata, S. anthelmia*. Each value, mean of the two film tickness, 100 and 150 µm (n = 8).

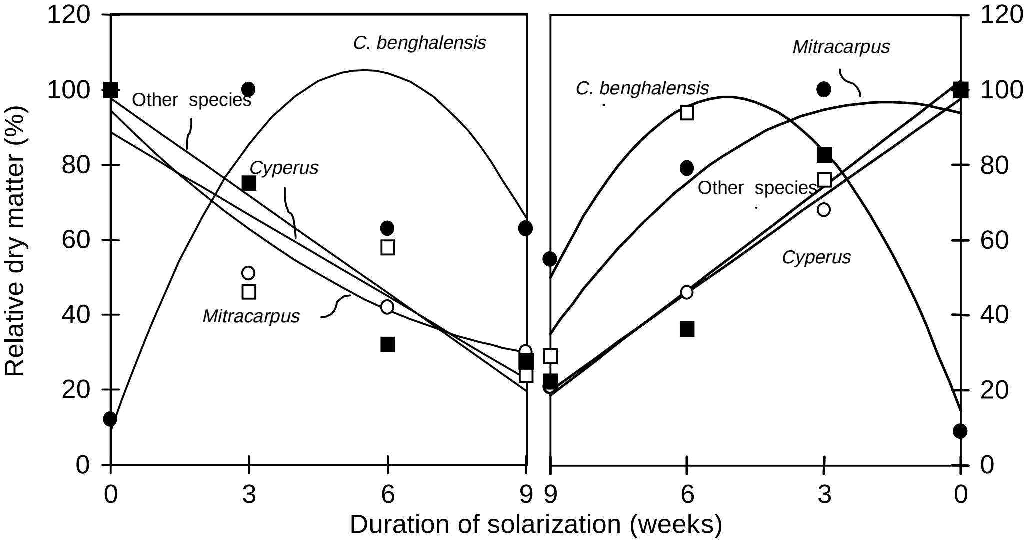

FIG. 2. Relative weed dry matter and relative density at 45 days after film removal. Relative weed dry matter: *Cyperus* (-O-), y_r = 88.60 – 7.30t, R^2 = 0.85; *C. benghalensis* (-●-), y_r = 20.10 + 25.87t – 2.44t^2, R^2 = 0.66; *Mitracarpus* sp. (- -), y_r = 94.40 – 12.20t + 0.56t^2, R^2 = 0.80; other species (-■-), y_r = 97.73 – 8.67t, R^2 = 0.93; relative density: C*yperus* (-O-), y_r = 97.60 – 8.63t, R^2 = 0.99; *C. benghalensis* (-●-), y_r = 14.45 + 32.65t – 3.19t^2, R^2 = 0.87; *Mitracarpus* sp. (- -), y_r = 93.75 – 3.75t + 1.14t^2, R^2 = 0.75; other species (-■-), y_r = 102. 25 – 9.30t, R^2 = 0.95. Where t is the duration of solarization (weeks). The group designated as other species included: *M. verticillata* and *S. anthelmia*. Each value, mean of the two film tickness, 100 and 150 µm (n = 8).

increased from 0.2% to 3.2%, about 15 times, indicating that this weed was more important in solarized plots than in the unsolarized one.

In solarized treatments, the yield of marketable roots was about 100% over the unsolarized control (Table 3), which indicates that this technique may be useful for weed control and improving yield of carrots, mostly in agroecosystems that do not use herbicides for reducing weed competition, such as in organic agriculture. Solarization had no effect on root-knot nematode incidence. On average, about 20% of carrot roots were infested by these nematodes (*Meloidogyne* spp.) (Table 3). Ineffectiveness of solarization in controlling root-knot nematodes suggests that under the local experimental conditions PE mulching could be combined with other treatments to increase the spectrum of target organisms to be controlled. Notwithstanding the influence of the border effect on nematode control and possibly other pests should not be ruled out (Grinstein et al., 1995).

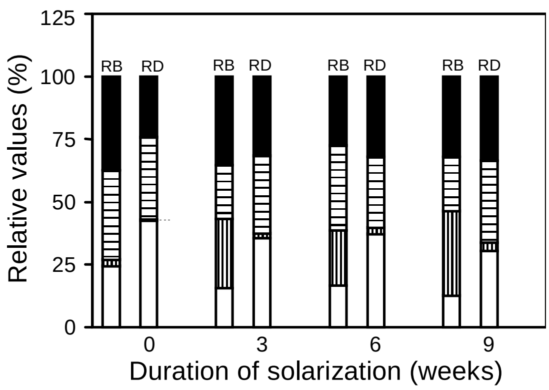

FIG. 3. Relative dry matter and relative density of dominant species: *Cyperus* sp. ( ), *C. benghalensis* (|||), *Mitracarpus* sp. (≡), and the group designated as other species (■) as a percentage of the total biomass or density of weed community. The group identified as other species included: *C. nictans* var. *paraguariensis*, *I. hirsuta*, *M. chamaedrys*, *M. verticillata*, *S. corniculata*, *S. anthelmia*. Symbols at top bars means: RB, relative biomass and RD, relative density.

TABLE 3. Average root production of carrot and roots attacked by nematodes at harvest time.

Solarization time (weeks)	Total root production		Roots attacked by nematodes	
	Fresh weight (g m^{-2})	Number of roots (n^{o} m^{-2})	Fresh weight (g m^{-2})	Number of roots (n^{o} m^{-2})
0	734.78	72.71	149.49	14.79
3	1389.37	127.92	304.31	21.67
6	1088.86	112.71	234.89	15.83
9	1585.21	129.17	417.66	24.17
F test	*	*	ns	ns

^{ns} and * Non-significant and significant at 5% of probability, respectively.

CONCLUSIONS

1. Soil solarization for nine weeks is effective for controlling more than 50% of weed species in the field.

2. Several weed species, about 40% of the weed community, are not affected by solarization.

3. Few species, about 5% of the weed flora, increase their populations after the solarization treatment.

4. The relative importance of some weeds in the weed community is affected by solarization.

5. Marketable yield of carrot is increased by solarization.

6. Soil tarping appears to be ineffective for controlling root-knot nematodes in sandy soil.

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