High Temperature Solarization for Production of Weed-free Container Soils and Potting Mixes

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Summary. **A double-tent solarization technique, which accumulates higher soil temperatures than solarization of open fields, was recently approved by the California Department of Food and Agriculture (CDFA) as a nematicidal treatment for container nurseries. Due to the need for broad-spectrum pest control in container nursery settings, this technique was tested to determine its usefulness as an herbicidal treatment. Laboratory-derived thermal death dosages (temperature × time) for several weed species important in California, including common purslane (*Portulaca oleracea*), tumble pigweed (*Amaranthus albus*), and black nightshade (*Solanum nigrum*), were previously determined and the data were used as guidelines for devising treatment duration in this study. In two field experiments conducted in 1999 and 2000 to validate the laboratory data, moist soil was placed in black polyethylene planting bags [3.8 L (1 gal) volume], artificially infested with seeds of the three test species, and subjected to 0 to 24 hours of double-tent solarization after reaching a threshold temperature of 60 °C (140 °F) (about 1.5 to 2.0 h after initiation of the experiment). In 1999, samples were removed at 2, 4, 20, and 24 hours after reaching the 60 °C threshold, then incubated to ameliorate possible secondary dormancy effects. Seeds failed to germinate in any of the solarized treatments. In 2000, samples were removed at 0, 1, 2, and 6 h after reaching 60 °C. Again, apart from the nonsolarized control treatment, all weed seeds failed to germinate at any of the sampling periods, in accordance with prior laboratory thermal death results. Reference tests to estimate effects of container size on soil heating showed that soil in smaller container sizes (soil volume) reached higher temperatures, and were maintained at high temperature [above 60 °C (140 °F)] for a longer period of time, than larger container sizes. The double-tent solarization technique can be used by commercial growers and household gardeners to effectively and inexpensively produce weed-free soil and potting mixes in warmer climatic areas.**

Maintaining soil and potting mixes free of weed infestation is essential for profitable nursery, greenhouse, field, and household production of high-value horticultural crops. In the case of nursery stock for farm planting, California law stipulates that growing media be free of economically important nematodes [State of California, 2002 (see Sections 3055-3055.6 and 3640)].

Producers of container nursery stock for planting in California currently use different methods for obtaining pest-free planting substrate. Some purchase virgin soil or various organic media from off-site locations, while others use various disinfestation methods, primarily methyl bromide fumigation. Steam treatment is an alternative to methyl bromide, but the steam generating equipment is expensive. Solarization, another alternative, is a mulching technique which employs passive solar heating to disinfest soil (Stapleton, 1996; Elmore et al., 1997). Solarization using two layers of polyethylene plastic film has been shown to accumulate more heat than treatment with the usual single layer, and to provide greater pest mortality (Ben-Yephet et al., 1987). Double-layer solarization has been especially useful in treating small volumes of nursery soil and potting mixes (Duff and Connelly, 1993; Kaewruang et al., 1989; Stapleton, 2000). A simple, double-tent solarization method that can provide soil temperatures in excess of 70 °C (158 °F) for pasteurizing soil or potting mixtures in warmer climatic areas was developed, tested, modified, and approved (Fig. 1) by the CDFA as a nematicidal treatment for container nursery plants (CDFA, 2002; Stapleton et al., 2001). The approved treatment is described as follows.

"Solarization of soil until the temperature of all of the soil reaches a minimum of 158 °F (70 °C) that is maintained for at least 30 continuous minutes, or a minimum of 140 °F (60 °C) that is maintained for at least 60 continuous minutes. Soil must be either in polyethylene planting bags or in piles not more than 12 inches high. Soil in piles must be placed on a layer of polyethylene film, disinfested concrete pad, or other materials that will not allow reinfestation of soil, and covered by a sheet of clear polyethylene film. An additional layer of clear polyethylene film must be suspended over the first layer to create a still air chamber over the soil to be treated. Soil moisture content must be near field capacity. Soil temperature at the bottom center of the pile or bag must be monitored and recorded to ensure that the minimum temperature of 158 °F (70 °C) for 30 min, or 140 °F (60 °C) for 60 min is achieved. Following treatment, the soil and containers shall be protected from reinfestation by nematodes" (Stapleton et al., 2001).

We previously reported on development of a thermal death database to predict efficacy of solarization for six weed species commonly encountered in California (Stapleton et al., 2000a). The database included relatively high temperatures [50 to 70 °C (122 to 158 °F)] that may be attained during the double-tent solarization technique (Stapleton et al, 2000b). This paper describes two field experiments testing double-tent solarization for elimi-

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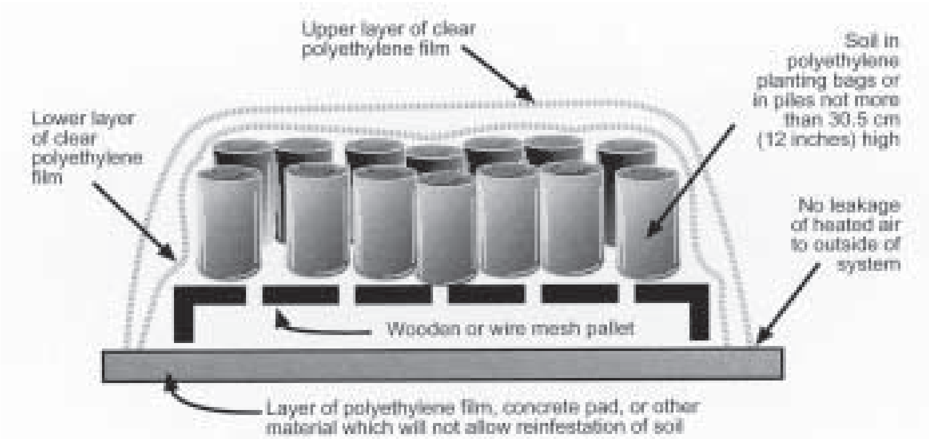

Fig. 1. Schematic representation of the double tent solarization technique used for these studies (adapted from California Dept. of Food and Agriculture, 2002).

nation of weed seed from container soil and potting mixes. Two additional field trials were done to determine effects of container size (soil volume) and composition on soil temperature during double-tent solarization.

Materials and methods

WEED SPECIES AND PREPARATION. The three weed species used for experimentation were common purslane, tumble pigweed, and black nightshade. For sample bag preparation, fifty seeds of each species were mixed with about 11 g (4 oz) of field soil and placed in organdy (nylon mesh fabric) squares, which were gathered and tied tightly with string. One bag of each of the three weed species was then placed in the center of each black polyethylene nursery bag filled with a Hanford sandy loam/Typic Xerothents field soil (soil volume 3.8 L). Polyethylene bags were watered to saturation and allowed to drain to field capacity overnight to begin seed imbibition before starting the solarization treatment. Additionally, five black polyethylene bags containing seeds of each species were prepared identically and left in the laboratory at ambient temperature [about 23 °C (73 °F)] to serve as controls.

SOLARIZATION TREATMENT. Five steel-mesh pallets [about 1.3 m × 1.3 m × 12.7 cm (4.3 ft × 4.3 ft × 5 inches) high] were placed 0.7 m (2.3 ft) apart in a north–south orientation in a field at the University of California Kearney Agricultural Center (KAC) in the central San Joaquin Valley [lat. 36°36'N, long. 119°30'W, 108.3 m (355.3 ft) elevation]. A sheet of 4-mil-thick [0.1-mm (0.004-inch)] black polyethylene film covered the soil beneath the pallets. Four black polyethylene bags, each containing organdy fabric bags of weed seeds of each experimental species were randomly distributed on each pallet. Soil temperature at the center of the soil mass in the polyethylene bags was monitored with a Hobo micrologger (Onset Computer Corp., Pohasset, Mass.) placed in a fifth bag on each pallet. Air temperature and solar radiation were monitored via California Irrigation Management Information System (CIMIS) meteorological station 39 (Parlier.A; Fresno County) located at KAC, about 200 m (656 ft) from the experiment site. Bags on pallets were covered with a sheet of 1-mil-thick [0.025-mm (0.001-inch)] transparent polyethylene film that was anchored on all sides with soil. Two metal hoops were placed over each plastic-covered pallet. A second sheet of the transparent film was stretched over the hoops, creating a tent with about 23 cm (9 inches) space between the two plastic layers, and anchored on all sides as before.

SAMPLE INCUBATION. A polyethylene bag containing soil and weed seeds was removed from each pallet at four intervals (2, 4, 20, and 24 h in 1999; 0, 1, 2, and 6 h in 2000) after soil temperature in the center of the bags reached a threshold temperature of 60 °C. In 1999, following removal from the pallets, bags were taken to the laboratory and left intact at ambient temperature for 48 h. The organdy bags of weed seeds were removed from all the polyethylene bags (treated and control) and placed in covered, plastic vegetable crispers in an unlighted incubator (Revco Scientific, Inc., Asheville, N.C.) at about 7 °C (45 °F) for 12 weeks to minimize the possibility of secondary dormancy (Taylorson, 1970). Bags of weed seeds were then removed, opened, and the contents placed in a petri dish on a disk of Whatman #1 filter paper, moistened with deionized water, and placed in covered plastic vegetable crispers. The

Fig. 2. Soil and air temperatures during double-tent solarization of 3.8-L (1-gal) polyethylene bags on (A) 27–28 Aug. 1999 and (B) 20 July 2000. The 60 °C (140 °F) and 70 °C (158 °F) treatment thresholds are indicated [°F = 1.8(°C) + 32].

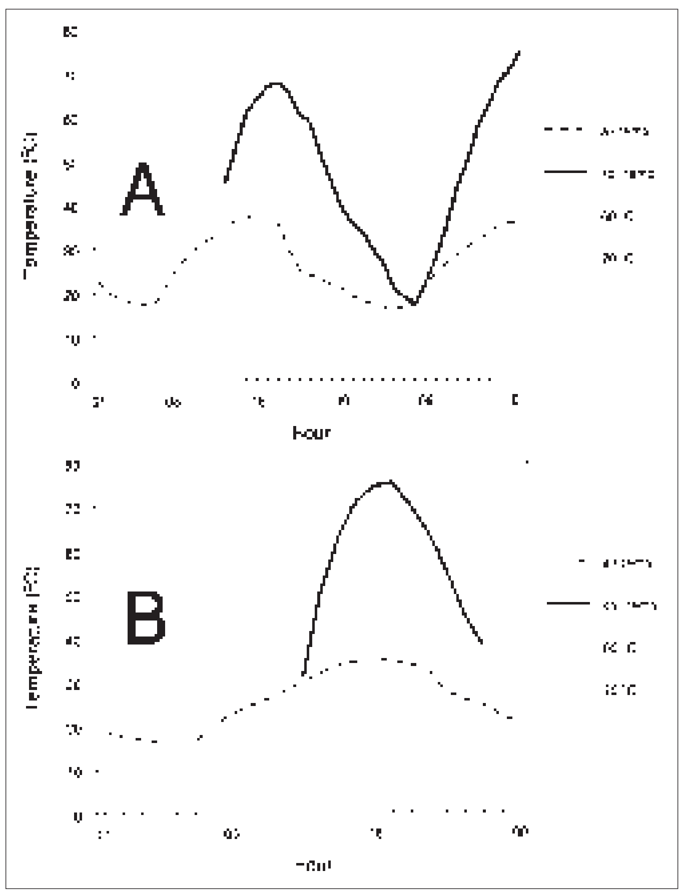

Table 1. Effect of high-temperature solarization on germinability of weed seeds, Parlier, Calif., 1999–2000.[z]

Weed species	Germination Control (%)	Solarized (h)[y] 2	4	20	24
27–28 Aug. 1999					
Tumble pigweed	25	0	0	0	0
Common purslane	20	0	0	0	0
Black nightshade	38	0	0	0	0
20 July 2000		**0**	**1**	**2**	**6**
Tumble pigweed	71	0	0	0	0
Common purslane	19	0	0	0	0
Black nightshade	25	0	0	0	0

[z]Germination values are means of five, 100-seed replications for the controls; and of five, 50-seed replications for solarized treatments. Seeds were placed in field soil within organdy bags during treatment. All germination values in solarized treatments are different from control values at $P < 0.01$ according to Student's t test.
[y]Hours after the soil temperature reached at least 60 °C (140 °F).

crispers were placed into an incubator adjusted to a diurnal cycle of 16 h at 30 °C (86 °F) and 8 h at 20 °C (68 °F), with exposure to a fluorescent grow light during the 30 °C-cycle. Deionized water was added to petri dishes as needed during incubation to maintain adequate moisture. In 2000, organdy bags were immediately removed from polyethylene bags at each sampling time to prevent residual heating, and left intact in the laboratory at ambient temperature overnight. The following day, samples were prepared and incubated to test germination as described above.

Germination data. Petri dishes were examined periodically and germinated seeds were counted and removed. Seeds were considered to have germinated when the radicle had emerged and the plumule elongated to 3 mm (0.12 inch). Germination counts were done at intervals of 10, 12, 15, 20, 27, and 30 d after seeds and soil were placed in petri dishes and moistened.

Effect of container size (soil volume) and composition on soil heating. Soil was collected as described above and placed in four different containers: 3.8-L, 8-mil-thick [0.2-mm (0.008-inch)] black polyethylene bags (Hummert International Corp., Earth City, Mo.); and 3.8-L, 7.6-L (2-gal), and 18.9-L (5-gal) black polypropylene pots (Nursery Supplies, Inc., Chambersburg, Pa.) to obtain comparative temperature data. Containers were filled with soil and solarized as described above, but without addition of bags of weed seed. As described previously, temperatures were continuously monitored with microloggers, two per container size. Two experiments were conducted: 11–16 Aug. 2000 and 16–17 Sept. 2000).

Results and discussion

Soil and air temperature and solar radiation accumulation. In 1999, experimental exposure of weed seeds to solarization began at 1300 HR on 27 Aug. and ended at 1500 HR on 28 Aug. Soil temperature at the beginning of the experiment (soil in black polyethylene bags but not enclosed in the tents) was 32 °C (90 °F). Soil temperatures in black polyethylene bags on the double-tented pallets (Fig. 1) reached maxima of 68 and 75 °C (154 and 167 °F) on 27 and 28 Aug., respectively; and a minimum of 16 °C (61 °F) during the 24-h period of treatment (Fig. 2A and B). The 60 °C threshold temperature imposed for timing of weed seed heat dosage was reached at 1500 HR (2 h after starting solarization); treatment continued for 24 h after the temperature threshold was reached. During the treatment period, air temperature reached diurnal maxima of 38 and 36 °C (100 and 97 °F); and a minimum of 17 °C (63 °F). Solar radiation totaled 275 and 256 W·m^{-2} (567.6 and 528.4 Langleys/d) at 2 m (6.6 ft) height on 27 and 28 Aug., respectively. Weed seed samples incubated for 24 h after achieving the initial 60 °C soil temperature

Table 2. Air temperature[z], solar radiation[y], and maximum soil temperature[z] in various container sizes (soil volume) and composition during double-tent solarization, Parlier, Calif., 2000.

Expt.	Max/min air temp (°C)[x]	Solar radiation (W·m^{-2})[x]	Max soil temp (°C) [minutes above 60 °C (140 °F)] 3.9-L (1-gal) bag	3.9-L (1-gal) pot	7.8-L (2-gal) pot	19.3-L (5-gal) pot
1 (August 2000)						
11	34/13	319	64 [264][w]	67 [336]	63 [232]	63 [216]
12	36/16	319	66 [300]	69 [368]	64 [280]	65 [268]
13	37/15	319	65 [288]	69 [368]	64 [280]	64 [268]
14	37/14	308	65 [288]	68 [360]	64 [264]	65 [252]
15	37/16	302	66 [320]	69 [376]	64 [288]	65 [276]
16	38/15	299	66 [320]	69 [368]	64 [280]	65 [264]
2 (September 2000)						
16	32/13	238	68 [280]	67 [272]	63 [184]	57 [0]
17	34/14	236	69 [296]	69 [288]	nd[v]	58 [0]

[z]°F = 1.8 (°C) + 32; minutes above 60 °C in brackets.
[y]W·m^{-2} = 2.1 Langleys/d.
[x]Data from California Irrigation Management Information System (CIMIS) Station #39 ("Parlier A") located 100 m (328.1 ft) from site of experiment.
[w]Values given are mean of two replications.
[v]nd = no data.

threshold accumulated 10.1 h above 50 °C, 7.0 h above 60 °C, and 1.3 h above 70 °C, whereas samples incubated for 20 h accumulated 10.1 h above 50 °C and 4.2 h above 60 °C. Samples incubated for 2 or 4 h above the 60 °C threshold also accumulated 1 h above 50 °C during the diurnal heating/cooling cycle.

In 2000, weed seeds were heated by solarization beginning at 1215 HR on 20 July and terminating at 1930 HR the same day. Soil temperature at the beginning of the experiment was 34 °C (93 °F); the 60 °C soil temperature threshold was reached at 1330 HR (1.25 h after initiation). Based on 1999 results that showed zero weed seed viability at any of the sampling times, duration of solarization treatments in 2000 was limited to 6 h after the 60 °C soil temperature threshold was reached. Soil temperature in the center of the black polyethylene bags reached a maximum temperature of 75 °C between 1609 and 1649 HR. During the treatment period, air temperature reached a maximum of 36 °C; solar radiation on 20 July totaled 335 $W \cdot m^{-2}$ at 2 m (6.6 ft) height. Weed samples incubated for 0 h above the 60 °C threshold accumulated 26 min above 50 °C; samples incubated for 2 h above 60 °C also accumulated 31 min above 70 °C; and samples incubated for 6 h above 60 °C also accumulated 4.2 h above 70 °C.

WEED SEED GERMINATION. In both the 1999 and 2000 experiments, all seeds failed to germinate after solarization within the 30 d incubation period (Table 1). Weed seeds from the control treatment either germinated (Table 1) or were considered viable after the gentle pressure test (Taylorson, 1970) or tetrazolium assay (Grabe, 1970), maintaining the same viability tested before the experiment. Previous laboratory experiments with the same weed species used in this study (Stapleton et al., 2000a) showed that none could survive more than 20 min at 70 °C, while the time of exposure at constant 60 °C necessary to kill all seeds did not exceed 1 h for tumble pigweed, 2 h for black nightshade, or 3 h for common purslane. At constant 50 °C, exposure times needed for 100% seed mortality ranged up to 114 h (tumble pigweed).

Results from the field experiments demonstrated that, even after the minimal dosage (1 h above 50 °C, then 2 h above 60 °C), all seeds failed to germinate for any of the species tested. These data generally agreed with laboratory thermal death results (Stapleton et al., 2000a), although the field and laboratory experiments differed in two important ways. First, temperatures in the laboratory study were constant, whereas diurnal heating occurred in the field; and second, the thermal death study was conducted in washed silica sand, while seeds in the field study were incubated in natural field soil.

EFFECT OF CONTAINER SIZE (SOIL VOLUME) AND COMPOSITION ON SOIL HEATING. Although the temperature-sensing instrumentation used in these container size experiments was not replicated sufficiently to allow proper statistical analysis, reference temperature data obtained showed the influence of container size on both extent and duration of temperature maxima (Table 2). As would be expected, soil in the smaller container sizes (soil volume) reached higher temperatures, and were maintained at high temperature (above 60 °C) for a longer period of time, each day of treatment. These reference data are of value in determining soil volumes which can be successfully treated, with respect to prevalent climate, meteorologic conditions, day length, etc. However, individual users will need to conduct similar tests under their particular conditions.

The double-tent solarization technique may serve as an effective and low-cost alternative to methyl bromide or steam disinfestation for commercial or hobby growers of container-grown plants in warmer climates around the world. It is especially suitable for production of weed-free container soils in developing countries.

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