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Effect of Steam and Solarization Treatments on Pest Control, Strawberry Yield, and Economic Returns Relative to Methyl Bromide Fumigation

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***Abstract*. The phase-out of methyl bromide as a soil fumigant for strawberry (*Fragaria ×ananassa*, Duch.) and increasingly strict regulations of all fumigants suggest that non-fumigant methods of soil disinfestation are needed. In warm climates, solarization controls soilborne pests, but fog and lower summer soil temperatures in coastal California render it unsuitable for pest control relative to chemical fumigation. The first objective of this study was to test the efficacy of steam in controlling soil pests in strawberry production. The second objective was to determine if combining solarization with steam in coastal California would achieve greater pest control and higher yields compared with steam or solarization used alone. The final objective was to determine the economic feasibility of steam and solarization treatments relative to MBPic fumigation. Field studies were conducted at Salinas, CA, in 2007–2008 and in 2008–2009 growing seasons. Treatments included MBPic 67/33% v/v at 392 kg·ha^{-1}, untreated control, solarization, steam, and steam + solarization. For steam + solarization plots, beds were solarized for 2 weeks before and 2 weeks after steam application. Before application of a clear film for solarization, beds were irrigated so the soil moisture was optimal for solarization. Steam was injected into the beds to reach soil temperatures to 70°C or higher up to a depth of 25 cm for 20 min. Soil temperatures during steam and solarization treatments were monitored. Control of soil pests was measured using pathogen and weed propagule bioassays in all treatments. After the 4-week treatment period, 'Albion' strawberry was transplanted in all plots. After transplanting, weed density, weed fresh biomass, and hand weeding time were recorded periodically in each treatment over the cropping season. Weed seed viability in steam and steam + solarization-treated plots was the same or lower than MBPic standard fumigation. Compared with MBPic fumigation, solarization alone was less effective in controlling weeds or reducing the hand-weeding time. Steam and steam + solarization treatments resulted in weed control similar to MBPic fumigation. Only certain steam treatments reduced the number of *Verticillium dahliae* Kleb. microsclerotia similar to the MBPic fumigation at 15-cm depth with no reductions at greater depths. There were no significant differences among treatments in 2007–2008 with regard to yield, but in 2008–2009, yields from steam treatments were comparable to the MBPic-treated plots. Economic analysis performed for the 2008–2009 season showed that net returns from steam or solarization treatments were less than MBPic treatment.**

California accounts for 85% of strawberry (*Fragaria ×ananassa*, Duch.) production in the United States and ≈20% of worldwide production [U.S. Environmental Protection Agency (USEPA), 2009a]. Most of the 16,107 ha under strawberry cultivation in California is in the southern and central counties along the coast, where the climate favors year-round production and harvest [U.S. Department of Agriculture–Economic Research Service (USDA-ERS), 2005, 2010]. High land prices often make it economically difficult to implement crop rotation with strawberry cultivation, resulting in high pest pressures (Duniway, 2002a). Since the 1960s, strawberry producers in California have depended on a mixture of two soil fumigants, methyl bromide (MB), and chloropicrin (Pic) for weed and pathogen control. MB fumigation in strawberry fields has been among the largest uses in California (USDA-ERS, 2000).

MB has been classified as a Class I stratospheric ozone-depleting chemical. Under the Montreal Protocol, the use of MB for fumigation in the United States after 2005 is permitted only through critical use exemption (Anbar et al., 1996; USEPA, 1993). For California strawberries, technically and economically feasible alternatives to MB are needed for control of pathogens such as *Verticillium dahliae*, *Pythium* spp., *Rhizoctonia* spp., and *Phytophthora* spp., root-knot (*Meloidogyne* spp.) and sting nematodes (*Belonolaimus* spp.), and weeds such as nutsedge (*Cyperus* spp.) and winter annuals (USEPA, 2009a). In 2008, a 14% reduction in gross revenue was estimated for California strawberry growers using alternatives vs. those using MB (USEPA, 2009b). Alternative fumigants to MB include Pic, 1,3-dichloropropene (1,3-D), metam sodium, and methyl iodide (Duniway, 2002b). Each of these fumigants has their advantages and disadvantages, and none is a complete replacement for MB (Shaw and Larson, 1999). Besides their inability to provide the spectrum of pest control achieved by MBPic use, these fumigants have to comply with ever increasing regulations. These regulations prohibit the use of fumigants on acreage sufficiently close to "sensitive sites" such as schools and houses, limit application methods and timing, restrict total annual fumigant use, and restrict the use of a specific fumigant in a geographical area, among other restrictions. In addition to direct effects on fumigant use, compliance costs are increasing, reducing growers' net returns.

Solarization is a non-chemical approach widely used in tropical regions to treat infested soils. The potential of solarization for pest control in temperate and subtropical regions, including Arizona, California, Florida, North Carolina, and Texas in the United States, has also been examined, but its efficacy is found to be variable in these regions and not always effective as MB fumigation (Chellemi et al., 1994; Hartz et al., 1993; Ristaino et al., 1991). Solarization may not control all pests and its pest control efficacy is likely to decrease with increasing soil depths (Hartz et al., 1993; Stapleton et al., 2000). Soil solarization is initiated by covering the soil with clear film for a period of 4 to 6 weeks. The best season to practice solarization is summer, which corresponds to the period between May and September in the Central Valley in California and between May/June to August/September in coastal California (Elmore et al., 1997). Pathogens such as *Verticillium* spp., *Rhizoctonia solani*, *Fusarium oxysporum*, and *Sclerotium rolfsii* can be controlled through solarization (Katan, 1984). Solarization controlled common purslane (*Portulaca oleracea* L.), hairy crabgrass [*Digitaria sanguinalis* (L.) Scop.], and pigweeds (*Amaranthus* spp.) in Central Greece and has potential to control other annual weed species (Hartz et al., 1993; Vizantinopoulos and Katranis, 1993). Perennial weeds, bulbous weeds, and those with a hard seedcoat are difficult to control through solarization (Linke, 1994). In coastal California, the effect of solarization on soil pests is inconsistent as a result of the presence of a marine fog layer and low summer soil temperatures.

Steam has long been used in nursery and greenhouse crop production systems to control soilborne pests, and studies have shown that most plant pathogens, insects, and weeds will die when moist soils are heated to maintain temperatures of 65°C or greater for 30 min (Baker and Roistacher, 1957). Pullman et al. (1981) found a linear relationship between soil temperatures and time needed to kill most soil pathogens. Subbarao and Hubbard (1996) showed that constant temperatures of 35°C for 45 d reduced *V. dahliae* microsclerotia numbers by 70%. Steam applications have been also been performed in orchards and in forests (Moyls and Hocking, 1994; Norberg et al., 1997). However, steam application over large areas is limited by its high fuel costs, slow speed, and amount of labor required (Melander and Jørgensen, 2005). To minimize fuel costs during steam operation, we hypothesized that a combination of solarization with steam may have beneficial additive and synergistic effects on pest control than steam or solarization used alone.

The objectives of this study were to: 1) test the efficacy of steam in controlling soil pests in strawberry production; 2) to determine if combining solarization with steam in coastal California would achieve greater pest control and higher yields compared with steam or solarization used alone; and 3) to determine the economic feasibility of steam and solarization treatments relative to MBPic fumigation.

Materials and Methods

Studies were conducted in the 2007–2008 and 2008–2009 growing seasons at the USDA-ARS research facility in Salinas, CA (lat. 36°4′ N, long. 121°3′ W, elevation ≈47 m). The soil at the study site was a Chualar sandy loam (fine loamy, mixed, thermic, Typic Argixeroll) with a pH of 6.5 and organic carbon content of 0.7%. This site has been used for strawberry production for the last 10 years and is fumigated with Pic, 1,3-D, and MB, typically every other year. The experimental design was a randomized complete block with six replicates in 2007–2008 and four replicates in 2008–2009. Plots were one raised bed 1.3 m wide × 6.1 m long in 2007–2008 and 1.3 m wide × 15.2 m long in 2008–2009. Irrigation in the beds was supplied by two drip tapes (Toro Ag, El Cajon, CA) spaced 13 cm apart and placed at a soil depth ranging from 2 to 5 cm. Drip emitters were spaced 30 cm apart and flow rate set at 1 $L \cdot h^{-1}$ at 70 kPa.

Treatments included an untreated control, MBPic standard mix 67/33% v/v at 392 $kg \cdot ha^{-1}$, solarization alone, steam alone, and steam + solarization. For the untreated control, the beds were left without fumigation, solarization, or steam. MBPic was applied pre-plant through the drip system in 40 mm of water on 29 Aug. in 2007–2008 and on 3 Sept. in 2008–2009. Solarization was initiated pre-plant by covering the beds with a clear standard polyethylene film (Guardian 1.2 mL; Guardian AgroPlastics, Tampa, FL). In plots that were to be solarized or steamed, the beds were irrigated to levels sufficient to promote heat transfer before treatment application. Pre-treatment moisture level in the soil was considered sufficient when the soil crumbled easily after being squeezed in the hand (Baker and Roistacher, 1957). Solarization was conducted from 24 Aug. to 21 Sept. in 2007–2008 and from 28 Aug. to 21 Sept. in 2008–2009. Steam was generated using a Sioux steam SF-20 diesel fired steam generator (Sioux Corporation, Beresford, SD) and was supplied to raise and maintain the soil temperature to 70°C or higher for 20 min up to 25-cm depth. After 20 min, steam disinfestation was discontinued. For steam + solarization treatment, beds were solarized 2 weeks before and 2 weeks after steam application. For the 2007–2008 growing season, steam treatments were applied on 6, 7, 10, and 11 Sept. 2007 and from 15 through 17 Sept. 2008, for the 2008–2009 season.

In 2007–2008, steam was delivered to the beds using a 1.3 wide × 6.1-m long steam blanket (Syn-Tex, Winnipeg, Manitoba, Canada). In 2008–2009, two methods that allowed for sub-surface soil steaming were tested. It was expected that these methods would reduce the time needed to steam treat plots compared with sheet steaming (blanket) and improve temperature range in the deeper soil layers (Runia, 2000). One method included injecting steam into a 5-cm-diameter polyethylene pipe with 0.3-cm diameter holes spaced every 20 cm apart on the pipe serving as outlets for steam onto the beds. The pipe was buried post-bed formation by forming a trench, laying the pipe in the trench at 20- to 25-cm depth from the soil surface, and re-filling the trench with field soil. The second method consisted of using 12.5-cm-diameter, 30-m long flexible mesh hoses, which were equipped with 20-cm steel spikes at 25-cm spacing down the hose (Syn-Tex). Spikes were inserted at full length into the soil and the hoses were connected to the steam generator for treatment. For the steam alone treatment, the clear film was painted white to minimize any solarization effect on beds.

Soil temperatures during the steam and solarization process were monitored in all treatment plots except MBPic, using Hobo U12-008 temperature sensors (Onset®, Pocasset, MA) at 5-, 15-, and 30-cm depths. A single Hobo temperature sensor was installed toward the center of each treatment plot bed. Soil temperature during steaming was also monitored by installing Bimetal thermometers (REOTEMP Instrument Corporation, San Diego, CA) at several locations in the plot to determine if the target temperature was achieved. An estimation of the amount of fuel consumed during steam treatment applications was performed for 2008–2009. 'Albion' strawberry was planted on 7 Nov. 2007 for the 2007–2008 growing season and on 16 Nov. 2008 for the 2008–2009 growing season. Cultural practices of the commercial grower were followed during the growing season.

Weed control assessment. Weed control was assayed by four methods: 1) bioassays of weed propagule viability; 2) weed density counts; 3) fresh shoot and root biomass of weeds; and 4) hand weed timing by commercial farm workers. For viability bioassays, 25 seeds of common chickweed [*Stellaria media* (L.) Vill.], common purslane, little mallow (*Malva parviflora* L.), and 10 yellow nutsedge (*Cyperus esculentus* L.) tubers were placed in 8 × 12-cm heat-sealed nylon mesh bags (Delnet, Middletown, DE). In addition to these weed species, 25 weed seeds of common knotweed (*Polygonum arenastrum* Jord. ex Boreau) were included in the 2008–2009 growing season. Common chickweed and common knotweed seeds were obtained from Herbiseed, U.K., and common purslane, little mallow and yellow nutsedge were gathered from agricultural fields near Salinas, CA. Four seed bags were buried per plot, two bags in the bed center, at the depths 5 and 15 cm, and two along the edge of the bed at the same depths. Post-treatment, bags were removed and seeds were assayed in the laboratory using a tetrazolium viability assay as described by Peters (2000). Weed densities were determined by taking a count of all weed species within each plot. Time to hand weed the length of each plot by a single person was recorded twice over the growing season, and the fresh shoot and root biomass of the harvested weeds was recorded.

V. dahliae *control.* In 2008–2009, in addition to weed seed viability, the effect of treatments on *V. dahliae* control was assessed. Soil samples infested with *V. dahliae* were taken from a grower's field in Watsonville, CA, thoroughly mixed, and aliquoted into mesh bags (Bag PQ218 7.5 cm × 15 cm sewn with a hole size of 10 μm) (Delstar Technologies, Inc., Middletown, DE) to weigh 100 g. Bags were tied onto a nylon string and buried at 45-, 30-, and 15-cm soil depths in the center of the

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bed. Post-treatment, the mesh bags were retrieved and air-dried in paper bags for ≈28 d. The air-dried soil was passed through a 425-μm (40-mesh) sieve. Ten grams of sieved soil from each sample was placed in screw-capped plastic vials and 2.5 mL of methionine (Sigma M-9500, St. Louis, MO) (0.0075 $g \cdot mL^{-1}$ distilled H_2O) solution was dispensed into the vial. The vials were then incubated at 30°C for 7 d and air-dried at room temperature (23 ± 1°C) for the same period. All air-dried soil from the vial was then poured into a mortar and pulverized gently to break the clods. The pulverized soil was plated onto five plates each using the Anderson sampler technique (Butterfield and DeVay, 1977) on modified NP-10 medium (Kabir et al., 2004). The plates were incubated for 21 d in the dark at room temperature (23 ± 1°C). After incubation, the surface of each plate was gently washed under a stream of water to remove soil. The numbers of microsclerotial colonies of *V. dahliae* on each plate were counted under a stereoscope at 10× to 20× (Kabir et al., 2004). The density of microsclerotia was expressed as the number of propagules/gram dry soil. The number of microsclerotia by treatment was converted to a percent of internal standard untreated controls.

Strawberry crop phytotoxicity and yield data. Visual crop injury assessments for strawberries (0 = no injury and 10 = dead plant) were made on 12 Feb. and 3 Apr. 2008 for the 2007–2008 growing season and on 16 Jan. 2009 for the 2008–2009 growing season. Strawberry harvests occurred one to two times a week from 18 Apr. to 22 Aug. for the 2007–2008 growing season and from 31 Mar. to 10 Oct. 2009 for the 2008–2009 growing season. Harvested fruits were graded into marketable (fresh market grade) and nonmarketable (culls).

Statistical analysis. Owing to the different number of treatments between seasons, data for each season were analyzed separately. Data were tested for normality and transformed with $\log_{10}(x)$ and $\log_e(x)$ when necessary to normalize variance. Data were analyzed using PROC GLM in SAS (SAS Institute Inc., Cary, NC). For the weed propagule viability data, treatment, location on the bed, and the depth of the propagule were independent factors. Treatment effects were determined on weed control and strawberry yield. Fisher's protected least significant differences were used for means comparison. Where transformed data were analyzed, reported means have been back-transformed.

Economic analysis. Data regarding yields, weeding and application times, machinery and equipment costs, and treatments from the field trial were paired with the 2008 fresh strawberry price reported for Monterey County (Monterey County Agricultural Commissioner's Office, 2009) and cost data obtained from a 2010 University of California Cooperative Extension cost study for fresh market strawberries in Monterey County (Bolda et al., 2010). Capital equipment was assumed to have a 5-year lifespan. The diesel-powered steam generator was assumed to be capable of treating 5 hectares per year. A partial budgeting analysis was used. Under this approach, only components of costs and revenues that change across study treatments are evaluated.

Results

Weed propagule viability and V. dahliae *survival.* In the 2007–2008 growing season, common chickweed viability was influenced by treatment × location and treatment × depth interactions (Table 1). Common chickweed viability in steam and MBPic treatments were the lowest at both levels of interaction. In solarization treatments, common chickweed viability was lower at the edge than at the bed center. Common chickweed viability was higher at 15 cm deep than at 5 cm deep in the solarization treatment. The treatment main effect influenced common purslane and yellow nutsedge viability (Table 1). Common purslane and yellow nutsedge viability in steam treatments were comparable to the MBPic fumigation and significantly lower than untreated control or solarization alone. Solarization alone did not reduce viability of these weed species as compared with untreated control. For little mallow, the treatment × location effect was inconsistent with viability of little mallow being higher in the edge of the bed vs. the center in the case of solarization, but the effect was reversed in the steam + solarization treatment. For little mallow, steam treatments reduced viability to a greater extent than the MBPic treatment. Solarization alone reduced viability of little mallow compared with untreated control and was as effective as MBPic fumigation.

In 2008–2009, seed viability of all tested weed species and yellow nutsedge tuber viability was influenced by treatment main effect (Table 2). Steam treatments were effective in reducing viability of common chickweed, common knotweed, common purslane, and yellow nutsedge equivalent to the MBPic treatment. Solarization alone also reduced viability of common chickweed, common knotweed, and little mallow as compared with untreated control. For little mallow, steam treatments were more effective than the MBPic treatment, and solarization alone was as effective as MBPic standard fumigation. Other weed species were not controlled by solarization alone in comparison with MBPic fumigation.

Table 1. Effect of treatment, location, and depth, on weed seed and yellow nutsedge viability at Salinas, CA, in 2007–2008.

	Common chickweed[z]					Little mallow		
	Center	Edge	5 cm	15 cm	Common purslane	Center	Edge	Yellow nutsedge
Treatment					Viability (%)			
Control	63.5 a[y]	64.7 a	68.0 a[y]	60.1a	87.2 a[x]	66.7 a[y]	74.0 a	27.7 a[x]
MBPic	0.0 c	0.0 c	0.0 c	0.0 c	8.5 b	36.7 bc	38.0 bc	10.3 b
Solarization	60.6 a	40.0 b	35.8 b	64.8 a	80.7 a	31.0 c	48.0 b	35.6 a
Steam (blanket)	0.0 c	0.0 c	0.0 c	0.0 c	0.0 b	7.0 de	0.7 e	8.3 b
Steam (blanket) + solarization	0.0 c	0.0 c	0.0 c	0.0 c	3.8 b	12.3 d	0.0 e	4.6 b
Treatment *P* values	0.0142		<0.0001		<0.0001	0.0041		<0.0001

[z] For common chickweed, the treatment × location and treatment × depth interactions were significant. For little mallow viability, the treatment × location interaction was significant.

[y] Means with the same letter across locations or depths for a weed species are not significantly different according to the least significant difference test at $P \leq 0.05$.

[x] Means with the same letter within a column are not significantly different according to the least significant difference test at $P \leq 0.05$.

Table 2. Effect of treatment on weed seed and yellow nutsedge viability at Salinas, CA, in 2008–2009.

	Common chickweed	Common knotweed	Common purslane	Little mallow	Yellow nutsedge
Treatment			Viability (%)		
Control	50.2 a[z]	82.0 a	38.3 a	80.7 a	31.9 a
MBPic	4.3 c	11.5 c	0.8 b	40.3 b	4.4 b
Solarization	32.5 b	61.7 b	51.7 a	42.3 b	30.0 a
Steam (pipe) + solarization	8.1 c	12.8 c	4.2 b	13.2 c	8.8 b
Steam (spikes) + solarization	0.3 c	1.0 c	0.0 b	0.0 d	2.5 b
Steam (spikes)	0.0 c	0.0 c	0.0 b	1.8 d	1.3 b
Treatment *P* values	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z] Means with the same letter within a column are not significantly different according to the least significant difference test at $P \leq 0.05$.

In 2008–2009, reductions in the number of *V. dahliae* microsclerotia in steam (pipe) + solarization and steam (spikes)-treated plots at 15-cm depth were comparable to MBPic fumigation (Table 3). However, at greater depths, none of the other treatments provided reductions in the number of *V. dahliae* microsclerotia obtained with MBPic fumigation. Steam + solarization treatments were no more effective than steam alone in the attrition of *V. dahliae* microsclerotia.

Weed fresh biomass, density, and hand-weeding time. Treatment effect on weed fresh biomass, weed density, and hand-weeding time in both seasons was highly significant (Table 4). In the 2007–2008 growing season, weed fresh biomass and density were the lowest in steam treatments and MBPic treatment. Time to hand weed plots was the least in steam and steam + solarization treatments. Solarization alone was effective in reducing weed biomass, density, and the weeding time as compared with untreated control but was less effective in controlling weeds than steam treatments or MBPic fumigation. Steam + solarization treatment did not improve weed control over steam alone. Predominate weeds in the field plots in the 2007–2008 season were common chickweed, common groundsel [*Stellaria media* (L.) Vill.], and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.].

In 2008–2009, treatment effect on weed biomass, density, and hand-weeding time was significant (Table 4). Weed biomass, density, and hand-weeding time were the lowest in steam and MBPic treatments. Solarization alone was effective in reducing weed biomass, density, and weeding time as compared with the untreated control plots, which had the highest weed population, but solarization alone was not as effective as steam or MBPic treatments for reducing weed density and hand-weeding time. Hand-weeding time in steam (pipe) + solarization was slightly higher than steam (spikes) treatments. In 2008–2009, predominate weeds were common purslane, shepherd's purse, redroot pigweed (*Amaranthus retroflexus* L.), common groundsel, common sowthistle (*Sonchus oleraceus* L.), burclover (*Medicago polymorpha* L.), and Southern brassbuttons [*Cotula australis* (Sieber ex Spreng.) Hook. f.].

Crop phytotoxicity and strawberry yields. No crop injury was noted in any of the treatments during either growing season. In the 2007–2008 growing season, there were no differences in the strawberry yields among treatments at $P = 0.05$ (Table 5). However, in the 2008–2009 growing season, steam and steam + solarization treatments had strawberry yields equivalent to or slightly higher than the MBPic-treated plots. Untreated control and solarization treatment had the lowest strawberry yields.

Fuel consumption. Fuel cost estimated in 2008–2009 showed steam (pipe) + solarization to be most efficient among the three steam treatments used in our study. Fuel cost for steam (pipe) was at $7,124/ha. Steam treatment costs from both spike treatments were estimated at over $19,000/ ha. These estimates were based on the diesel price of $0.88/L.

Economic analysis. As a result of availability of fuel consumption data for 2008–2009 alone, the economic analysis was performed only for that growing season. Based on the partial budget analysis, neither steam nor solarization treatments performed as well as MBPic. Table 8 summarizes the analyzed costs, gross returns, and the difference in net returns between each treatment and MBPic.

Losses under the steam treatments are driven primarily by treatment costs. For all treatments, differences in hand-weeding times and in gross revenues and harvesting costs (both affected by yields) are noticeably smaller than the differences in net revenues. This is consistent with the statistical analysis of these items. Recalling the earlier analysis of results, there was no statistically significant difference between MBPic and the steam treatments in terms of hand-weeding time or yields. Equipment costs, including the cost of pipes or spikes and the prorated cost of the diesel steam generator, are either slightly lower than the custom application cost of MB in the case of pipe or just over half the cost in the case of spike.

The losses under solarization relative to MBPic are driven by multiple factors. Solarization had a higher hand-weeding time and lower yield than MBPic. The difference in hand-weeding time was statistically significant, whereas the difference in yields was not. However, the treatment cost for the solarization treatment was negligible. Overall, the difference in net returns for the two treatments was less than either the cost of the custom MBPic treatment or the hand-weeding costs for the solarization treatment.

Discussion

Pre-plant soil steam and steam + solarization treatments resulted in the most effective pest control and generated strawberry yields similar to MBPic. Steam treatments killed weed seed and yellow nutsedge tubers and reduced weed biomass, weed densities, and hand weeding to levels achieved with MBPic. Steam controlled *V. dahliae* microsclerotia at 15-cm depth similar to the MBPic standard, but at 30- and 45-cm depths, steam did not control *V. dahliae*. In 2008–2009, yield from steam treatments was comparable to MBPic-treated plots. Solarization alone did not control weeds or reduce the hand-weeding times as effectively as MBPic. Integration of solarization with steam did not accrue benefits beyond those obtained with

Table 3. Effect of treatment on survival of *Verticillium dahliae* microsclerotia at 15-, 30-, and 45-cm depths at Salinas, CA, in 2008–2009.

	Depth		
	15 cm	30 cm	45 cm
Treatment	Viability (%)[z]		
Untreated control	53.9 a[y]	82.8 a	50.8 a
MBPic	0.4 c	4.3 c	14.2 b
Solarization	53.5 a	81.0 a	67.3 a
Steam (pipe) + solarization	8.9 c	41.4 b	46.5 a
Steam (spikes) + solarization	33.6 ab	59.5 ab	50.8 a
Steam (spikes)	10.8 bc	47.6 ab	55.8 a
Treatment *P* values	0.0001	0.0001	0.0008

[z] Percent control calculated as percent of internal control.

[y] Means with the same letter within a column are not significantly different according to the least significant difference test at $P \leq 0.05$.

Table 4. Cumulative weed fresh biomass, weed density and hand-weeding time at Salinas, CA, in 2007–2008 and 2008–2009 strawberry growing seasons.

	Weed fresh biomass		Weed density		Hand-weeding time	
	2007–2008	2008–2009	2007–2008	2008–2009	2007–2008	2008–2009
Treatment	(kg·ha^{-1})		(no./ha)		(h/ha)	
Untreated control	18,221.2 a[z]	3,155.5 a	3,873.8 a	898.0 a	1,509.3 a	1,097.1 a
MBPic	4,215.5 c	851.3 bc	175.4 c	92.9 c	429.5 c	249.3 cd
Solarization	10,106.6 b	1,435.4 b	1,033.4 b	413.4 b	783.8 b	631.1 b
Steam (blanket)	2,536.0 c	x	102.3 c	x	255.3 d	x
Steam (spikes)	x[y]	732.7 c	x	83.0 c	x	241.7 d
Steam (blanket) + solarization	3,315.1 c	x	167.5 c	x	352.6 cd	x
Steam (spikes) + solarization	x	962.5 bc	x	96.1 c	x	295.3 cd
Steam (pipe) + solarization	x	1,192.3 bc	x	169.8 c	x	399.6 c
Treatment *P* values	<0.0001	0.0014	<0.0001	<0.0001	<0.0001	<0.0001

[z] Means with the same letter within a column are not significantly different according to the least significant difference test at $P \leq 0.05$.

[y] "x" indicates that the treatment was not evaluated during the growing season.

steam alone such as the levels of pest control and crop yield.

Elmore et al. (1997) and Katan (1981) reported that many weed species including common chickweed and little mallow can be controlled through solarization and our findings are consistent with these previous research reports. For little mallow, solarization was as effective as MBPic application. This similarity between solarization and MBPic treatments could partly be the result of inadequate efficacy of MBPic against little mallow and burclover (Daugovish and Fennimore, 2008; Wilhelm and Paulus, 1980). In the 2007–2008 growing season, lower common chickweed viability observed with solarization treatments at 5 cm relative to 15-cm depth is also consistent with the established patterns observed with solarization wherein the effect is greatest at or near the soil surface, and its effect is progressively reduced with increasing depths (Stapleton, 2000). However, the effect of solarization on weed viability across the horizontal plane (bed center vs. the edge) was inconsistent. The contours of the film on the raised bed that determine its contact with the soil surface could affect the solarization efficacy across the bed surface. Thus, inconsistencies in temperature accumulation across the soil surface may partly explain inconsistent effects on weed viability across the beds. Solarization alone provided better control of common knotweed compared with the untreated control. Solarization was ineffective against common purslane and yellow nutsedge. Controlling a summer annual such as common purslane is more difficult, because it is insensitive to temperature ranges as compared with winter annuals such as common chickweed (Elmore et al., 1997). Viability of common purslane was unaffected at 46°C or less and in general temperatures of 50°C or greater are needed to kill most weed propagules (Dahlquist et al., 2007; Webster, 2003). The highest temperatures achieved with solarization treatment in our location were only 44 and 46°C at 5-cm depth during the warmest times of the day in 2007–2008 and 2008–2009 growing seasons, respectively (Tables 6 and 7). These temperatures were not sustained for sufficient time to reduce the viability of common purslane seed.

Solarization alone was ineffective in reducing *V. dahliae* microsclerotia in soil. This is in contrast to the findings reported by Hartz et al. (1993), who showed control of *V. dahliae* to a depth of 25 cm by solarization compared with untreated control. The differing locations where the two studies were conducted along with the duration of solarization may explain the contrasting results obtained. The study by Hartz et al. (1993) was conducted in southern California where the potential to accumulate heat units is greater, and the solarization process was carried out from late July through September. Steam through pipe and spikes can effectively increase soil temperatures to a depth of 25 cm or less during treatment application. As a result, *V. dahliae* at depths of 30 to 45 cm was not effectively controlled by steam treatments. At shallow depths of 15 cm, steam (pipe) + solarization performed better than steam (spikes) + solarization.

Solarization alone did not reduce weed biomass, densities, and hand-weeding time to levels comparable to MBPic. Because solarization is a passive process, treatment efficacy depends on the weather conditions. When cool conditions persist like in coastal California, solarization may best work in combination with other effective soil pest control tools (Stapleton, 2000). In plots exposed to solarization, although soil temperatures of 40°C or greater were retained for a greater duration as compared with steam alone, the temperatures did not reach high enough to sufficiently control pests, or improve strawberry yield over untreated control (Tables 6 and 7). Soil temperatures of 70°C or greater were reached by steam treatments in both seasons. In both seasons, the cumulative duration for which temperatures were 40°C or greater in the steam + solarization treatments (Tables 6 and 7) did not provide an added advantage over steam alone in controlling pests or improving strawberry yields.

Superior weed control and crop yield in strawberry production achieved by pre-plant soil steam treatment was consistent with our other study (Samtani et al., 2011). In an Oriental hybrid lily trial (*Lilium* sp.), weed density in steam-treated plots was comparable to MBPic standard fumigation (Rainbolt, 2011). Pre-plant steam treatment applications have shown a positive effect on the crop growth and yields of other horticultural crops (Luvisi et al., 2006; Moyls et al., 1994). Several studies have investigated the effect of soil steaming on soil quality or microbial communities. Some studies report steaming to have little to no lasting negative impact on soil quality or soil microbial communities (Jäderlund et al., 1998; Norberg et al., 2001; Zackrisson et al., 1997), whereas others report a more significant change in soil microbial activity resulting from steam sterilization (Tanaka et al., 2003; Yamamoto et al., 2008). Duration and method of steaming, the soil temperatures attained during steaming, and soil organic matter content could account for these differences in findings.

Current challenges that limit the adoption of steam treatment to large-scale field production include fuel consumption, labor, and application time. These factors affect the economic viability of the technology for growers. Fuel costs estimated from our study are exceedingly high, barring the fuel costs of the steam (pipe) treatment, which is comparable to the current MBPic application cost of $8500/ha. Application time increases labor and fuel costs. It also reduces the number of hectares that can be treated using the diesel-powered steam generator each season, which increases the per-hectare cost of the generator. Reductions in application time would reduce all of these costs.

Table 5. Cumulative strawberry yields for 2007–2008 and 2008–2009 growing seasons at Salinas, CA.

	Yield	
	2007–2008	2008–2009
Treatment	(g/plant)	
Untreated control	264.7	610.4 c[z]
MBPic	348.6	857.9 ab
Solarization	291.9	720.0 bc
Steam (blanket)	353.2	x
Steam (blanket) + solarization	395.6	x
Steam (pipe) + solarization	x[y]	813.0 ab
Steam (spikes) + solarization	x	912.6 a
Steam (spikes)	x	970.9 a
Treatment *P* values	0.0936	0.0033

[z] Means with the same letter within a column are not significantly different according to the least significance difference test at $P \leq 0.05$.

[y] "x" indicates that the treatment was not evaluated during the growing season.

Table 6. Soil temperatures achieved during treatment application at Salinas, CA, in the 2007–2008 strawberry growing season.

	High temp[z]	Avg temp	Time 40°C or greater
Treatment	(°C)		(h)
Untreated control	33.1	18.4	0
Solarization	43.9	28.2	31.3
Steam (blanket)	99.7	34.1	5.8
Steam (blanket) + solarization	86.0	31.0	50.0

[z] All temperature readings taken at 5-cm depth over 4-week period except for steam readings that are taken over a 24-h period.

Table 7. Soil temperatures achieved during treatment application at Salinas, CA, in the 2008–2009 strawberry growing season.

	High temp[z]	Avg temp	Time 40°C or greater
Treatment	(°C)		(h)
Untreated control	39.8	22.0	0
Solarization	46.1	28.3	53.0
Steam (pipe) + solarization	81.3	28.2	64.2
Steam (spikes) + solarization	78.5	25.7	40.7
Steam (spikes)	80.6	24.1	11.7

[z] All temperature readings taken at 5-cm depth over 4-week period except for steam readings that are taken over a 24-h period.

Table 8. Differences in costs and returns at Salinas, CA, in the 2008–2009 strawberry growing season.

	Treatment costs				Other costs			Net revenues
	Equipment	Labor	Fuel	Custom	Hand weeding	Harvesting	Gross revenues	Difference from MBPic
Treatment	($/ha)							
Untreated control	—	—	—	—	13,034	25,495	55,974	–13,090
MBPic	—	—	—	8,522	2,962	35,832	78,671	—
Solarization	—	130	44	—	7,497	30,073	66,025	–3,075
Steam (pipe) + solarization	8,236	1,276	7,124	—	4,747	33,957	74,553	–12,142
Steam (spikes) + solarization	4,619	1,276	19,893	—	3,508	38,117	83,687	–14,506
Steam (spikes)	4,619	1,276	19,317	—	2,871	40,552	89,033	–11,534

Although economic performance of solarization was improved over that of the steam treatments, solarization still resulted in lower net returns than MBPic standard fumigation. Furthermore, the limitations of solarization in coastal California are well recognized. Given the differences in yield and pest control efficacy between solarization and steam, additional research and technological advancements to reduce the cost of steam application is a more promising way forward for developing economically and technically feasible alternatives to MBPic. As it currently stands, the steam treatment is a promising option in buffer areas where fumigants cannot be used as well as a tool for organic production systems.

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