Evaluation of a Mobile Steam Applicator for Soil Disinfestation in California Strawberry

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Abstract. Steam-disinfestation of soil as an alternative to chemical fumigation was investigated in both research and commercial strawberry (*Fragaria × ananassa* Duch.) production field trials at four sites over 2 years (2011–13) using new prototype commercial application equipment: a tractor-drawn device that physically mixed the steam with the soil as it passed through the shaped planting beds. Results included significant suppression of weeds and soilborne pathogens equal to commercial chemigation of chloropicrin with 1,3-dichloropropene (Pic-Clor 60). Also, the combination of steam treatment with soil amendments of mustard seed meal (MSM; two of four trials included treatment), a fertilizer and source of additional organic matter, showed very favorable strawberry production in terms of yield as well as weed and pathogen control. Soil nitrogen-containing ions were monitored at two of the sites and the MSM treatment significantly elevated available soil nitrates by the time of transplanting as did the steam treatment alone, but only significantly at one of the sites.

The common practice currently in California strawberry production to control soilborne pests such as weed seeds, insects, nematodes, and pathogens is to use chloropicrin with 1,3-dichloropropene [Pic-Clor (TriCal, Inc., Hollister, CA), InLine (Dow AgroSciences, Indianapolis, IN), Telone (Dow AgroSciences, Indianapolis, IN), Tri-Form (TriCal, Inc., Hollister, CA)] through the drip irrigation tape before transplanting strawberries into the fruiting fields. Fumigants are not available

for organic producers or in portions of conventional fields where fumigation is restricted by buffer zones extending 35 m or more outward from neighborhoods and schools. These restrictions, and similar limits on other fumigants such as dazomet, metam sodium, or metam potassium, are why non-fumigant alternatives are needed to control soilborne pests.

Early pest control with steam can be traced back to 1893 (Johnson, 1946). Beyond cardinal temperature data documented for various pathogens (Togashi, 1949), thermal death curves were determined (Bega and Smith, 1962; Nelson and Wilhelm, 1958; Smith, 1923; van Koot and Wiertz, 1947). Time required at given temperatures to eliminate weed seeds was similarly found (Dahlquist et al., 2007; Melander and Jørgenson, 2005; Peruzzi et al., 2012). Soil moisture factors affecting heat conduction (Gay et al., 2010; Minuto et al., 2005) and also water imbibition by targets as a pre-condition to increase efficacy of this

treatment have been explored (Horowitz and Taylorson, 1983). Using prior knowledge on steam, a tractor-drawn steam boiler was engineered to inject steam 35 cm into raised strawberry beds for a threshold minimum temperature of 70 °C for 30 min, a level of heating sufficient to control pathogens and most weed seeds (Baker, 1957). Part of the novelty of this technological advance was the physical mixing of steam with soil supported by a separate study showing that soil agitation during steaming can improve efficiency (Miller et al., 2014).

Adoption of steam disinfestation of field soils has been hindered by fuel consumption, labor, and application time required (Samtani et al., 2012). Despite steam providing weed control, pathogen suppression, and yields similar to fumigated strawberries, Samtani et al. (2011, 2012) found that the higher equipment and fuel costs reduced net returns to the grower choosing steam over fumigation. Also, with treatment taking 49 h·ha⁻¹ with current technologies, the treatment was too slow to be considered a practical alternative to fumigation. Similar findings with equivalent pest suppression and marketable crop returns in cut flower production were observed when comparing steam with standard fumigants (Rainbolt et al., 2013). However, when the intensive requirements for fuel and labor were considered, they prevented recommendation of steam as a viable replacement to fumigants in cut flower production in California until better efficiency in time and energy required is achieved.

Mineral nutrient balance in agricultural soils can be adversely impacted by excessive steam treatment (Dawson et al., 1965; Simon-Silvestre, 1967; Sonneveld, 1979; van Koot and Bakker-Beer, 1949). Microflora and -fauna considered beneficial to soil and plant health have also been shown to be sensitive to over-treatment (Fenoglio et al., 2006; Roux-Michollet et al., 2008, 2010; Tanaka et al., 2003; Warcup, 1951a, 1951b; Yamamoto et al., 2008). Modern application of this treatment has gained the common language of soil pasteurization rather than soil sterilization to acknowledge efforts to not over-treat with steam.

Initial objectives were to evaluate a newly designed mobile steam applicator for efficacy in soil disinfestation of weeds and pathogens in raised strawberry beds as well as for strawberry safety and fruit production. Efficacy and crop safety had been shown for several stationary sources in our field steaming research (Fennimore et al., 2013; Rainbolt et al., 2013; Samtani et al., 2011, 2012) but the new steamer had no such evaluations because it had just been completed. Monitoring soil nitrogen, pH, and electrical conductivity (EC) was added in the following season at two sites to address fertility impact and crop safety questions with respect to nutrient balance. Also, amendments of pelletized MSM were made before steam treatment of the beds in 2012. This supplemental carbon and nitrogen source (4.9N–3.4P–1.2K), or the active oils derived from it, have been

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investigated for weed suppression (Samtani et al., 2011) and antimicrobial activity (Walker et al., 1937) and emerged from earlier trials (Fennimore et al., 2013; Shennan et al., 2014) in combination with steam as a promising field practice meriting further study.

Materials and Methods

Applications of steam to strawberry fields.

Steam was applied by a tractor-towed wagon with a propane-fueled Clayton 100 HP steam generator (Clayton Industries, City of Industry, CA) capable of steaming one 1.32-m wide raised bed per field pass. Fuel consumption was 14,600 L·ha⁻¹ (2288 m³·ha⁻¹ soil treated). This is 6.42 L·m⁻³ or 1.55/10⁵ BTU/m³. Baker (1957) listed a figure equivalent to 1.48/10⁵ BTU/m³ to raise soil temperatures from 15.6 to 71.1 °C with steam, so our results are comparable. Machine, fuel, and labor costs were estimated at U.S. \$13,521 per hectare based on the single-bed prototype in Dec. 2011, at the beginning of these trials, and efficiencies have been improved from that time. Steam was injected and mixed into the soil through a bed shaper equipped with two rototillers, each with 24 steam injection tines delivering steam through injection nozzles in the tines, which were distributed at 90° spacing about the tiller circumference and ≈10-cm spacing along the tiller shaft. Steam was also introduced into the bed shaper from the sides and top. The tillers were offset relative to the bed length and separated in depth by ≈10 cm as they were pulled through the formed beds. The bed shaper was adjustable in pitch and height, resulting in steam being delivered at

≈25- and 35-cm depths and also from 18 cm above the surface. The cross-sectional area of the formed bed treated was 36 × 91 cm (81-cm top width, 102-cm bottom width, 36-cm height) or 0.33-m² cross-section. The volume treated was 2460 m³·ha⁻¹. The height of the beds after steaming was 31 cm, likely as a result of soil shifting from the bed to furrow. Water was supplied to the steam generator through a 400-m long hose reel and was softened using commercial ion exchange canisters for boiler longevity (Culligan Water Conditioning, Salinas, CA). Insulation was used to maintain heat in the bed for a few minutes. In the 2011–12 growing season, this was accomplished by towing a 15.2 m × 1.7-m fabric blanket behind the steam applicator. This blanket was replaced by an insulating foam blanket (Rubberite Cypress Sponge, Santa Ana, CA) in the 2012–13 season as shown in Figure 1. The insulation helped maintain high-temperature retention time for 6 to 7 min before allowing the bed to begin cooling after steam application. The beds at all sites were covered from 1 to 14 d after treatments, after beds had cooled.

Soils included three series and four sites, so each soil–site combination was unique. In 2011, two trials were conducted, one at Salinas, CA, on 12 and 13 Oct. at the USDA/University of California research site (Spence) and the second at Watsonville, CA, on 25 Oct. at the California Strawberry Commission research site at the Monterey Bay Academy (MBA). At Spence, the soil was a Chualar sandy loam (fine-loamy, mixed, superactive, thermic Typic Argixerolls) with a pH of 7.2. At MBA, the soil was an Elder sandy loam (coarse-loamy, mixed,

superactive, thermic, Cumulic Haploxerolls) with pH of 6.1. At both sites, Pic-Clor 60 (56.7% chloropicrin, 37.1% 1,3-dichloropropene) was included as a fumigant standard at 280 and 392 kg·ha⁻¹ in Salinas and Watsonville, respectively. The trials were arranged in a randomized complete block design with five replications of 61 m of single beds at Salinas and four replications of 27 m of single beds at Watsonville. Sampling areas for yield, weeds, and other data are as described in tables. Spence was planted with variety ‘Albion’ on 28 Nov. 2011, and MBA was also planted with the same variety on 21 Nov. 2011. In 2012, the steam applications were repeated on 6 and 7 Sept. at a commercial research field (“The Company Ranch,” or TCR, Driscoll’s, Watsonville, CA) and at a grower field in Watsonville, off San Juan Road (SJR) on 8 and 10 Sept. Both fields’ soils were Salinas clay loam (fine-loamy, mixed, superactive, thermic Pachic Haploxerolls) with a pH of 7.3. TCR was planted with variety ‘Albion’ on 13 Nov. and varieties 123Q191 and 273M171 on 20 Nov. 2012, and SJR was planted with variety 49C129 on 1 Nov. 2012. All plants were certified (or in the case of TCR and SJR, approved), and therefore nursery fields were inspected and rogued of certain plants showing symptoms of pathogens before harvesting transplants.

Amendments of 3360 kg·ha⁻¹ pelletized MSM (Farm Fuels, Inc., Watsonville, CA) were made immediately before steam treatment of the beds in 2012, thus exposing the MSM to the heat of the steam treatment, but no fumigants were included in these two trials. Both 2012–13 sites used randomized complete block designs with four replications. Treated plots were 59 m of single beds for each replication at TCR and from 11 to 29 m of single beds at SJR. Sampling areas for data are described in tables of results. The TCR site had been covered with a legume/grain mix in Nov. 2011 followed by sorghum/Sudan grass in Apr. 2012 and then compost was applied at a rate of 22 t·ha⁻¹ in Aug. 2012. The SJR site had been bedded up with pre-plant prill fertilizer (18N–8P–13K) at 0.45 tons (metric)/ha.

Measures of temperature, weed control, pathogen control, soil nitrogen, yield. After passage of the steam applicator, soil temperatures in the plots were measured from within 1 to 2 min after passage for the next 2 h to 3 d with Hobo TMC6-HD temperature sensors using the U12-008 recorder (Onset, Pocasset,

Fig. 1. (Left) Clayton steamer treating strawberry beds. 2012 photograph shows foam insulation, water supply hose, and tractor to draw the single-bed prototype applicator. (Right) Same bed showing weed suppression after 27 d.

Table 1. Weed seed viability after treatment with Pic-Clor 60 or steam at two field sites near Watsonville, CA, in two production seasons, as determined by survival of weed seeds buried, recovered, and assayed for viability by tetrazolium.

	Common chickweed		Common knotweed		Little mallow		Yellow nutsedge	Annual bluegrass	Common purslane	Burning nettle
	MBA	TCR	MBA	TCR	MBA	TCR	MBA	MBA	TCR	TCR
Treatments	-----						Percent viable	-----		
Non-treated	69 a ²	83 a	96 a	95 a	95 a	85	45 a	66 a	83 a	93 a
Steam	2 b	0 b	6 b	8 b	72 b	58	0 b	1 b	0 b	1 b
Steam + MSM	—	0 b	—	8 b	—	60	—	—	2 b	10 b
Pic-Clor 60	4 b	—	0 c	—	63 b	—	0 b	86 a	—	—
P	0.0001	0.0001	0.0001	0.0018	0.0101	0.28	0.0002	0.0004	0.0001	0.0001

*Mean separations by Duncan's multiple range test, $P = 0.05$. Values based on four replications with two to three subsamples of 10 to 25 seeds (or tubers for nutsedge) each per replication.

MBA = Monterey Bay Academy; TCR = The Company Ranch; MSM = mustard seed meal.

MA). Sensors at several depths (15, 30, 45, and 60 cm at Spence, 2011–12, and at 5, 15, 25, and 35 cm at TCR and SJR, 2012–13) were installed in the strawberry beds as soon as the steam applicator passed.

Evaluation of weed control included both weed seed samples placed in the plots and control of resident weeds in the seed bank. Weed seed bags containing various dry seed or tuber samples as detailed in Table 1 were buried in soil at 15-cm depth from within 1 to 2 min after passage of the steamer at $\approx 35\%$ and 65% of the distance from the end of the plots. In 2011–12, two subsamples (weed seed bags) per plot were used at MBA. In 2012–13, two or three weed seed bags per replicated plot were placed at TCR. Weed seeds were removed from 3 to 14 d after treatment and tested for viability with tetrazolium (Cottrell, 1947) with parameters of 0.1% concentration, 25 °C, dark, 24 h. Weed densities and spectrum of weed species present in the field were measured periodically. Weeds in the strawberry planting hole, the only area not covered with mulch film, were collected during repeated hand-weeding events that took place at monthly to bimonthly intervals. Weeding times were recorded as described in Santani et al. (2012). Data on weed weight (fresh in 2011–12, dry weight in 2012–13) was recorded over the season to determine treatment impact on weeds surviving in the seed bank.

The presence and level of *Pythium ultimum* Trow was assayed from soil the second year at both sites immediately before treatment and again 28 d later by methods previously described in Klose et al. (2008). Endemic presence of *Macrophomina phaseolina* (Tassi) Goid. at the TCR site was found in the second year in the cultivar Albion allowing comparisons of treatments for management of this target pathogen. Data for incidence of this pathogen were by common isolation and culturing (potato dextrose agar) of surface-sterilized (ethanol:water, 7:3 v/v for 30 s) tissue samples from roots and crowns of affected strawberry plants.

Soil samples were composites of 10 to 20 cores (1.8×15 cm) from each plot collected from planting holes where strawberries would be transplanted or within 3 to 5 cm of strawberries after transplanting. Soil cores were collected from 1 h to 2 d before steam application and again for 8 to 10 weeks at varying intervals depending on site. They were air-dried on greenhouse benches for 2 weeks, ground with a mortar and pestle until they could pass through a #10 laboratory sieve (2-mm opening), and stored in paper bags until evaluated for soil pathogens, ions, or conductivity. These soil samples were assayed for $[\text{NH}_4^+]$ and $[\text{NO}_3^-]$, pH, and EC. Both nitrogen-containing ions were assayed by the corresponding ion-selective electrodes (Oakton Instruments, Vernon Hills, IL) in combination with a millivolt (mV) reader (Orion Aplus pH/ISE meter, Model 720A+; Thermo Fisher Scientific, Waltham, MA) by immersing 10-g soil subsamples (one subsample for $[\text{NH}_4^+]$, three subsamples for $[\text{NO}_3^-]$ to address higher variation between subsamples) in 40 mL deionized water in 50-mL capacity plastic centrifuge tubes prepared separately for each ion. Appropriate amounts of the respective ionic strength adjuster solutions were added as per manufacturers' recommendations, then the solutions were shaken for 30 min on a laboratory shaker, after which the tubes were placed in wire racks in a constant temperature bath during assays. Calibration curves were run every 2 h or less using standards held in the same temperature control bath. pH and EC were determined using a portable pH/EC/TDS meter (Hanna HI 9813-0 with HI 1285-0 probe; Hanna Instruments, Smithfield, RI) by preparing a saturated soil paste using deionized water from an ≈ 30 -g subsample of soil in a plastic cup and then immersing the sensor directly into the paste for readings.

Fruit yield was measured by a commercial harvest crew once or twice weekly. At MBA harvests were from sample areas of 34 to 35 plants per plot from 24 Apr. through 6 Sept.

2012 for a total of 39 harvest dates. Spence harvests spanned 28 Mar. through 15 Sept. 2012 from five replications of 34 to 36 plants each for 45 harvest dates. Fruit sample areas at TCR had 40 plants each per plot and were harvested from 6 Apr. through 19 Oct. 2013 (29 weeks), and SJR's harvest plots were also of 40 plants in each of four replications and harvests were from 27 Apr. through 19 Oct. 2013 (26 weeks). Number of harvests for this and prior site was confidential.

Data analysis. Data were subjected to analysis of variance, and mean separation was performed using the Duncan's multiple range test. Soil nitrogen ion levels were determined by one or three subsamples per soil sample ($[\text{NH}_4^+]$ and $[\text{NO}_3^-]$, respectively) reflecting level of subsample variation with corrections for drift of electrodes based on calibration against known standards every 2 h as per manufacturers' recommendations. Calculations were aided by MS Excel 2007 (Microsoft, Redmond, WA) and also ARM 7 (Gylling Data Management, Inc., Brookings, SD). Tabular values for evaluating probabilities were accessed from standard references (Geng, 1997).

Results

Representation of temperatures recorded at a single study site after steam application is shown in Figure 2. The surface temperature loss was offset in the 2012 trials with foam insulation. Closer analysis of data recorded for the 2012 applications (replicated with one or two sets of sensors at SJR and TCR, respectively) logging at all depths for each replication in the trial allowed for assessment of the level of temperature variation that may be encountered resulting from variability in tractor speed, soil moisture, time of day of application, and differential between surface and air temperature (Fig. 2). In one of the eight treated beds at TCR shown in the right panel of Figure 2, the original target of 30 min of 70 °C was not achieved at the 15-cm depth. This variation in temperature

Fig. 2. (Left) Temperature logs from field monitoring. Temperature profiles are means of eight replications that include steam treatments and steam + mustard seed meal (MSM) treatments. (Right) Variation in heating between plots (at the same field site as in left panel) to which steam was applied. Each replicated plot shows mean of two temperature sensors spaced at least 50 m apart.

Table 2. Cumulative season-long weed biomass, weed densities, and hand-weeding times at four sites over two seasons.

Treatments	Weed biomass ^z				Weed density				Hand weeding time			
	2011–12		2012–13		2011–12		2012–13		2011–12		2012–13	
	MBA	Spence	TCR	SJR	MBA	Spence	TCR	SJR	MBA	Spence	TCR	SJR
	kg·ha ⁻¹				10 ³ n/ha				h·ha ⁻¹			
Non-treated	114.6 ^y	433.3 a	90.1 a	0.9	44.0 a	89.7 a	250.3 a	2.5	79.2 a	219.6 a	412.2 a	22.4 a
Steam	6.3	16.7 b	1.3 b	1.1	3.0 b	17.8 b	5.1 b	1.2	44.4 b	80.3 b	29.2 b	16.9 b
Steam + MSM	—	—	12.4 b	2.0	—	—	14.9 b	1.5	—	—	51.5 b	18.3 b
Pic-Clor 60	5.1	154.3 b	—	—	2.5 b	42.0 b	—	—	31.9 c	97.4 b	—	—
P	0.0999	0.0127	0.0141	0.6329	0.0016	0.0027	0.0015	0.2586	0.0008	0.0007	0.0006	0.0292

^zBiomass data for 2011–12 sites was taken fresh for 2012–13 sites after oven-drying. Data were collected over different lengths. MBA: 7.6 m, Spence: 15.2 m; TCR: 6.1 m; SJR: 11.3 to 15.2 m.

^yMean separations by Duncan's multiple range test, $P = 0.05$. Values based on four (MBA, TCR, and SJR) or five (Spence) replications.

MBA = Monterey Bay Academy; TCR = The Company Ranch; SJR = a grower field in Watsonville, off San Juan Road; MSM = mustard seed meal.

indicates that success of the steam treatments will depend on control of steam delivery of sufficient temperature, duration, and depth to manage pests targeted.

Most weed seed samples placed in the fields were controlled by steam treatments, as shown in Table 1, with the exception of little mallow (*Malva parviflora* L.) at TCR. Reduction in viability of weed seed samples after exposure to steam or Pic-Clor 60 was recorded at MBA in 2011–12. Steam and steam + MSM controlled buried weed seeds at TCR in the 2012–13 growing season compared with the non-treated control. Annual bluegrass (*Poa annua* L.) seeds were not controlled by Pic-Clor 60 as shown in Table 1; however, the resident bluegrass seed bank was controlled by Pic-Clor 60 equally to steam at MBA (data not presented). As assayed in weed seed bags (Table 1), small seeded weeds, including common chickweed [*Stellaria media* (L.) Vill.], burning nettle (*Urtica urens* L.), annual bluegrass, and common purslane (*Portulaca oleracea* L.), and also yellow nutsedge tubers (*Cyperus esculentus* L.), were effectively controlled with steam treatment at both locations. A reduction in viability of hard seeded weeds such as common knotweed (*Polygonum arenastrum* Boreau) and little mallow was also observed at both locations for knotweed and at only the MBA location for little mallow.

Weed densities in the resident seed bank were reduced after steam, steam + MSM, and Pic-Clor 60 treatments when compared with the non-treated beds (Table 2) with the exception of the SJR site in 2012–13. Weeds encountered in commercial fields included 10 to 20 dominant species from each site but are presented as total weed densities in Table 2. These treatments reduced weeds by more than half at Spence in 2011–12, where predominant weeds included annual bluegrass, sowthistle (*Sonchus oleraceus* L.), bur clover (*Medicago polymorpha* L.), purple cudweed [*Gamochaeta purpurea* (L.) Cabrera], and little mallow, by more than 93% at MBA in 2011–12, where the main weed pests were annual bluegrass, chickweed, knotweed, lesser swinecress [*Coronopus didymus* (L.) Sm.], vetch (*Vicia* spp.), corn spurry (*Spergula arvensis* L.), and little mallow, and by more than 94% at TCR in 2012–13, where weeds were volunteer grains from the winter cover, swinecress, London rocket (*Sisymbrium irio* L.), shepherd's-purse (*Capsella*

Table 3. *Pythium ultimum* levels before and 4 weeks after steam application at two sites during the 2012–13 season.

Treatments	TCR		SJR	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
	Propagules (n/g)			
Non-treated	187.2 a ^z	97.4 a	29.0	112.6
Steam	80.8 b	8.6 b	22.3	74.1
Steam + MSM	105.0 b	3.8 b	33.2	1.4
P	0.0372	0.0488 ^y	0.8909	0.1260 ^x

^zMean separations by Duncan's multiple range test, $P = 0.05$. Values based on four replications.

^yProbability from transformed [$\sqrt{(y+0.5)}$] data to address heterogeneity of variance.

^xProbability from transformed [$\log(y + 1)$] data to address heterogeneity of variance.

TCR = The Company Ranch; SJR = a grower field in Watsonville, off San Juan Road; MSM = mustard seed meal.

bursa-pastoris L.), and little mallow. Little mallow is particularly difficult to eradicate using steam or Pic-Clor 60 with a sizeable fraction remaining viable in the seed bank. We previously reported high little mallow survival from fumigation in Fennimore et al. (2003). At the SJR site the weed densities were low for the non-treated controls in the 2012–13 season, so no treatment effects were observed for weed control. The results for suppression of weed biomass (Table 2) were significant at two of the sites, where the steam or fumigant reduced weed biomass by more than 64% at Spence in 2011–12 compared with the treatment means observed in the non-treated controls, and the steam treatments reduced weed biomass by more than 86% at the TCR site in 2012–13. Subsequent hand-weeding times were reduced significantly at all sites by steam, steam + MSM, and Pic-Clor 60 compared with non-treated beds (Table 2). These three treatments were equivalent in reducing labor at Spence, TCR, and SJR.

At the TCR site, *Pythium ultimum* was suppressed by steam and steam + MSM treatments in the 2012–13 season (Table 3). Combining steam and steam + MSM treatments at both sites (two treatments $\times$ four replications per treatment $\times$ two sites = 16 replications using steam), propagules per gram soil (ppg) were reduced (three of 16 replicated plots) or eliminated (10 of 16 plots) at both the TCR and SJR sites by the time of transplanting. Levels of this pathogen increased in two of 16 plots. In contrast, the levels of *P. ultimum* increased in two of eight non-treated plots and decreased in three of eight. At TCR, a *Macrophomina phaseolina* (charcoal rot) infestation allowed comparison of treated and non-treated plots for manage-

ment of charcoal rot, where the impact of this pathogen was significantly reduced by steam and steam + MSM treatments (77% and 64% reduction in disease, respectively; Fig. 3).

The pH and EC of the soil were assayed from all plots over the 8 to 10 weeks from treatment through transplanting at the TCR and SJR sites in the 2012–13 season, but no differences were detected (data not shown). On the other hand, differences were observed in the levels of soil nitrogen ion concentration in steam or steam + MSM treatments compared with non-treated beds. The likeliest explanation for the differences between sites was the presence of pre-plant fertilizer at SJR and none at TCR; the SJR site had a preplant fertilizer treatment and had a higher starting nitrogen concentration, whereas the TCR site used a rotation of incorporated legume/grain mixtures before planting to manage fertility.

Soil nitrate levels in Table 4 showed increases with steam + MSM treatments at the time of transplanting compared with non-treated beds. Steam + MSM increased soil nitrate in the first 2 weeks after treatment at the TCR site, but nitrate levels declined to a much lower level by 4 weeks after steam application. A similar increase for ammonium is in Table 4 but occurring at 4 weeks and settling to levels equal to (SJR) or higher (TCR) than in non-treated beds by the time of transplanting. Ammonium levels were higher in the steam + MSM treatments at both sites at 4 weeks after application compared with both the steam treatments and also the non-treated controls. Nitrate-to-ammonium ratios fluctuated over 8 weeks, ranging from high levels 10 d after treatments at the TCR site but reducing by the time of transplanting for steam + MSM at SJR and for steam at the TCR site. The ratios for the steam and

Disease progress of *Macrophomina phaseolina* in strawberry

Fig. 3. Disease progress curves for epidemic of strawberry charcoal rot caused by *Macrophomina phaseolina* at The Company Ranch in 2013 affecting U.C. variety 'Albion'. Values are percent loss over time (as rated by number of plants killed by disease). Mean separation by Duncan's multiple range test at $P = 0.05$ based on four replications of 72 to 74 plants each.

steam + MSM treatments at transplanting were higher than those in the non-treated beds. Data are presented as parts per million by mass of ions. For conversion, $[\text{NH}_4^+]$ is 18/14 [N] and $[\text{NO}_3^-]$ is 62/14 [N]. Nitrate-to-ammonium ratios are presented in Table 4 as molar equivalents: that is, $[\text{NO}_3^-] \cdot 18.039 \cdot ([\text{NH}_4^+] \cdot 62.004)^{-1}$.

Pre-plant steam treatments increased marketable yield of fresh berries for the season compared with the non-treated as shown in Table 5, with the exception being 'Albion' at MBA where treatment effects on yield were not significant. Significant fruit yield increases relative to the non-treated were: 50% at SJR for 49C129, 18% at Spence and 114% at TCR, both for 'Albion', and 80% for 123Q191 and 109% for 273M171 at TCR. Steam treatments produced yields similar to Pic-Clor 60 (MBA, Spence), and steam + MSM and steam had similar yields (TCR, SJR).

Discussion

The need for fumigant alternatives was the impetus for this research. Earlier studies with field steaming techniques for strawberry production were limited by stationary means of application, which included pipes, spikes, and insulating blankets and extensive labor input (Samtani et al., 2012). By physical mixing of steam with soil and automatic application, it is possible to treat strawberry beds at a steady pace with minimum labor input. In the current study, the target temperature of 70 °C was achieved and maintained for 30 min in all steam treated strawberry beds with an average applicator speed of 161 m·h⁻¹. This converts to 47 h·ha⁻¹, a speed too slow to commercialize as a result of the need for timely field treatment. The steam applicator design tested here may be a useful model for development of a commercial scale applicator with a higher capacity for treatment of buffer zones in production fields

adjacent to hospitals, schools, and other sensitive sites as well as organic production fields.

Thermal profiles confirmed previous observations that heat from steam moves by conduction in a predominantly upward direction from the point of application (Baker, 1957). The highest temperatures were achieved for the longest durations, not at the bottom of the soil profile where steam was introduced at 35-cm depth, but rather at a 15-cm depth (Fig. 2). Neither automation allowing mobility of the steam applicator nor depth of delivery of the steam changed conduction of heat energy delivered to soil by steam. The temperatures recorded after steam applications in the field were equivalent to the findings of several other studies (Gay et al., 2010; Pinel et al., 2000; Roux-Michollet et al., 2008). Also, variability of soil (moisture content, compaction, profile, etc.) within the field accounts for variation between treated plots in targeted delivery of heat (Fig. 2) and suggests the future design of the applicator addresses this variation with a temperature monitor and feedback system that can adjust either speed of travel and/or amount of steam applied. It would be desirable to incorporate feedback controls based on real time monitoring of temperature at each depth in future designs of steam application equipment. Also, depth of heat delivered will be important, because generally the uppermost few centimeters of the soil profile contain the seasonally significant weed seed bank (Shem-Tov et al., 2006), whereas the lower reaches of the root zone are of more concern for soilborne pathogens. Retention of target heat levels was increased by an average of 7 min by drawing a 15-m insulating blanket behind the applicator.

The profile of weeds susceptible to steam disinfection roughly corresponded to their seedcoat permeability with the more heat-resistant species of knotweed and little

mallow showing less consistent control with steam in the soil seed bank than easier to control species like chickweed, purslane, and nettle as indicated by Table 1. In most cases, weed control results with Pic-Clor 60 and steam were similar with both treatments better than the non-treated. Steam reduced the number of weeds at MBA, Spence, and TCR (Table 2). The reduction in weed biomass was significant at Spence and TCR. Treatment effects at the SJR site, which had very low weed pressure, were not significant. Results indicated Pic-Clor 60 and steam were equivalent in reducing the spectrum, mass, and the number of competing weeds. The reduction in hand labor required by steam, steam + MSM, and Pic-Clor 60 (Table 2) is a significant factor in containing costs. Of note, the savings in labor become greater with greater weed presence as revealed by comparison of the data (Table 2) from the least (SJR) to the most (TCR) impacted sites. At SJR, 18% to 25% reduction in labor afforded by the steam treatments increases to 88% to 93% reduction at TCR with intermediate savings of 44% (MBA) and 63% (Spence) reductions afforded by steam treatments at the progressively more infested sites.

Pythium ultimum was suppressed by both the steam and the steam + MSM treatments at the TCR site (Table 3), and the soil was apparently not recolonized at a pace damaging to strawberry production. Recolonization may have occurred in one of the 16 steamed plots in the 2012–13 season (data not presented). Also, data collected 48 h post-steaming (data not presented) showed these same soils to be completely *Pythium*-free at that point. Table 3 presents the treatment effects at transplanting, 4 weeks after treatment. The elimination then reappearance strongly supports recolonization as the explanation. This niche-filling of the relative void left after disinfestations by the most proximal and rapid colonists is a long-recognized phenomenon (Baker, 1962; Bollen, 1974; Rowe et al., 1977; Warcup, 1951b) with pathogens normally checked by a diverse community of competitors but able to re-establish rapidly if unimpeded. *Pythium ultimum* did not uniformly colonize the soil before the trial at either site, but pre-treatment inoculum was only significantly different between beds at TCR. Nevertheless, the near total elimination after treatment with steam or with steam + MSM is sufficient to show the effect these treatments offer in eliminating this pathogen. Uniform field distribution of a pathogen afforded by inoculation at protected research facilities was not an option at these commercial sites, so uniformity as a baseline was a desirable but unlikely condition for trial placement.

The infection by *Macrophomina phaseolina* at TCR allowed an evaluation of the effect of steam and steam + MSM on this pathogen. The significant suppression of plant loss to charcoal rot shown in Figure 3 might well account for the yield differences observed from August into October, but these yield differences were apparent by May. *Macrophomina* is soilborne and active at

Table 4. Mean soil nitrogen ion levels at two sites after steam application.

	SJR					TCR				
	8 Sept.	10 Sept.	17 Sept.	10 Oct.	7 Nov. 2012	6 Sept.	8 Sept.	17 Sept.	10 Oct.	14 Nov. 2012
	ppm NH ₄ ⁺									
Steam	44.8	21.4	5.5	9.3 b ²	3.8	5.1	7.2	6.9	6.6 b	5.5 b
Steam + mustard meal	33.4	33.0	7.5	25.2 a	4.3	5.5	14.7	10.5	24.7 a	15.8 a
Non-treated		20.2	4.5	4.5 c	3.7	6.3		6.3	6.7 b	6.5 b
	ppm NO ₃ ⁻									
Steam	320	96	418	282	169 b	73	57	168 b	111	131 b
Steam + mustard meal	122	90	682	321	308 a	70	72	704 a	159	271 a
Non-treated		101	410	250	125 b	65		57 b	129	56 c
	Equivalents (NO ₃ ⁻ :NH ₄ ⁺)									
Steam	7.3	1.7	27.9	9.7	12.6 b	4.7	3.0	7.5 b	6.0	7.1 ab ²
Steam + mustard meal	5.2	1.1	31.3	4.6	20.5 a	3.9	1.7	23.4 a	1.9	7.2 a
Non-treated		4.4	22.4	14.9	9.8 b	3.0		2.6 c	6.0	2.6 b

²Letters in figure are mean separations based on Duncan's multiple range test at $P = 0.050$. All means were based on four replications. Mean separations for the date where letters appear were significant.

³Separation for this date at $P = 0.053$. Soil nitrogen before treatments (6 Sept. for SJR, 8 Sept. for TCR) described in "Materials and Methods."

Table 5. Season-long marketable strawberry fruit yield at four sites and six trials.

Variety Treatments	2011–12		2012–13			
			TCR		SJR	
	24 Apr. to 6 Sept. 2012	28 Mar. to 15 Sept. 2012	6 Apr. to 19 Oct. 2013		27 Apr. to 19 Oct. 2013	
	Albion	Albion	Albion	123Q191	273M171	49C129
	Marketable fruit (t·ha ⁻¹)					
Non-treated	30.2	20.9 b ²	28.5 b ²	37.3 b ²	31.3 b ²	26.1 b ²
Steam	40.0	24.6 a	60.9 a	67.0 a	65.3 a	39.1 a
Steam + MSM	—	—	62.4 a	71.5 a	70.1 a	39.2 a
Pic-Clor 60	36.5	26.2 a	—	—	—	—
<i>P</i>	0.1570	0.0003	0.0017	0.0001	0.0003	0.0150

²Mean separations by Duncan's multiple range test, $P = 0.01$. Values based on four replications.

³Mean separations by Duncan's multiple range test, $P = 0.05$. Values based on five replications.

MBA = Monterey Bay Academy; TCR = The Company Ranch; SJR = a grower field in Watsonville, off San Juan Road; MSM = mustard seed meal.

higher soil temperatures (Zveibil et al., 2012), which does not occur until late in the season (August) when the disease occurs in the cooler northern coastal fruit production areas of California. The fact of some loss occurring in the steam and steam + MSM treatments suggests the effective inoculum resided lower in the soil profile, below the effective depth of disinfestation extending 35 cm with this applicator. It would require time for the roots to grow down to this depth, and the number of infections and time required for plant collapse have not been recorded for strawberry.

The higher yields observed in the steam and also in the steam + MSM treatments investigated are possibly the result of even greater pathogen suppression than was identified in these observations. It is well known that many root pathogens of strawberry decrease productivity at sublethal levels, either alone or in concert with others, including various species including *Colletotrichum acutatum* Simmonds (Daugovish et al., 2012), *Cylindrocarpum destructans* (Zinssm.) Scholten (Martin and Bull, 2002), *Iridiella lunata* P. E. Nelson & S. Wilh. (Nelson and Wilhelm, 1956), *Fusarium oxysporum* f.sp. *fragariae* Winks & Williams (Islas et al., 2011), *Pythium* spp. (Martin and Bull, 2002), and *Rhizoctonia* spp. (Martin, 2000), all of which have been reported from soils in this immediate vicinity.

Ammonium levels were elevated at TCR by the time of transplanting for the steam + MSM treatment compared with the non-treated

controls. TCR had no pre-transplanting fertilizer, so it began with a lower overall nitrogen level than SJR. Consistent at both sites, a significant elevation of soil ammonium was recorded ≈4 weeks after treatments for the steam + MSM treatment. The soil ammonium elevation at that time was significant for steam treatment only at SJR. This increase of ammonium then subsided by 8 to 10 weeks after steam applications to near pre-treatment levels but remained elevated statistically for the steam + MSM treatment at TCR, the site with no pre-transplanting fertilizer added.

Ammonium levels recorded were below concern for strawberry roots at temperatures encountered in California production areas. Detailed work by Ganmore-Neumann and Kafkafi (1983) showed effects of ammonium as a sole source of nitrogen became adverse only with increase of root temperature, appearing very slightly at 17 °C and more damaging at 25 and 32 °C, a condition that would not be typical in central coast California conditions until much later in the season (May to June), and the presence of any nitrate tempered these effects even more so. Similarly, other studies describing ammonium injury on strawberry required higher levels and temperatures (Choi et al., 2011; Claussen and Lenz, 1999). The ammonium levels as affected by steam treatment and steam + MSM are minimal with respect to central coast California strawberry culture.

Soil nitrate levels recorded were elevated by the steam + MSM treatments by 8 to 10 weeks after treatment compared with the

non-treated controls (Table 4). An increase of soil nitrate was recorded ≈10 to 11 d after application of steam or steam + MSM. Table 4 shows the increase occurred at SJR in the non-treated control as well but not at TCR. Increase in the non-treated control is likely the result of the presence and release by irrigation of pre-plant fertilizer at SJR that was not present at TCR. The elevation of nitrate by 8 to 10 weeks post-treatment, as shown in Table 4, significantly for steam + MSM at both sites and significant for steam at TCR where there was no pre-transplanting fertilizer differs from some results reported (Gelsomino et al., 2010; Tanaka et al., 2003; Yamamoto et al., 2008) who recorded a general decline in nitrate levels after application of steam but is consistent with those of Sonneveld (1979).

Nitrate-to-ammonium ratios were calculated from the data recorded and presented as equivalents (Table 4). Although largely reflective of the overall nitrate levels, the fluctuations, attributed by many as an indication of microbial community composition, are of some interest. The immediate depression in this ratio, which we recorded at 2 d after treatment in 13 of 16 steamed beds, is consistent with the findings of Roux-Michollet et al. (2008) and might be expected given explanations by others of increased microbial decomposition elevating ammonium levels combined with findings of others of an immediate lowering of soil nitrate levels (Gelsomino et al., 2010; Sonneveld, 1979; Tanaka et al., 2003; Yamamoto et al., 2008).

The latter effect was not consistently recorded in our study (see above). What differed in our results from those of Roux-Michollet et al. (2008) was the period after that initial depression. They recorded a subsequent increase in this ratio from 6 to 27 d after treatment with steam, or in non-treated soil, but more so in the latter. We also recorded this increase in the ratio from 2 to 11 d after treatments in treated and non-treated soils, but our study then recorded a reversal and lowering of this ratio in all steamed treatments by 4 weeks, then another reversal and elevation by the time of transplanting at 8 to 10 weeks. At TCR the nitrate-to-ammonium ratio was elevated significantly compared with the non-treated soil at transplanting for the steam treatment, and at SJR, the nitrate-to-ammonium ratio was elevated significantly compared with the non-treated soil at transplanting for the steam + MSM treatment.

It is apparent that the addition of MSM to soils before application of steam greatly increases fertility, as measured by levels of nitrogen-containing ions (Table 4). The higher levels of nitrates and ammonium recorded were expected with the MSM.

Fruit yields are dramatically improved by the application of steam and steam + MSM treatments using this mobile applicator (Table 5). Further research is recommended to understand the dynamics of this combination.

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