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Band Steaming for Weed and Disease Control in Leafy Greens and Carrots

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***Abstract.* Steam injected into the soil, raising soil temperatures to >70 °C for 15 to 20 minutes, will control weed seed and soilborne pathogens. The effect of this reduction in the weed seedbank viability results in weed control in the treated zone that can persist for several weeks or months. The effect of steam pasteurization of soil on weed seeds produces results similar to a preemergence herbicide. In our study, steam was applied to the soil to control weed seed and propagules of *Sclerotinia minor* and *Pythium* spp. Replicated field trials in carrot, lettuce, and spinach were conducted using two types of band steam applicators in 2020 and 2021. Data collected were soil temperatures after steam application, weed control, hand weeding times, diseased plant counts, pathogen populations in the soil, and crop yields. Poststeam soil temperature intervals >70 °C in the top 10 cm of the soil ranged from 67 to 176 minutes. Steam reduced weed densities by 64% to 100% and lowered hand weeding times by 23% to 91%. The reduction of *S. minor* sclerotia propagules after steaming was 69% to 95% compared with the no steam control. The percentage of lettuce plants infected with lettuce drop was reduced by 60% to 70% and the reduction of *Pythium* spp. propagules in the soil was reduced by 50% to 100% compared with the no steam control, respectively. Lettuce head diameters in steamed soils were 10% to 24% larger compared with the no steam control. Carrots grown in the steam-treated soil had a 10% greater root diameter than the no steam control. Steam increased lettuce yields in two of three trials 22% to 28% compared with the no steam control. Gross revenues for the steam-treated lettuce were $3231/ha higher than in the no steam control. The data suggest that band steam is a viable soil pest control treatment for vegetable crops.**

Vegetable crops have been grown commercially in the coastal areas of California since the early 1900s. These areas have fertile soils and a Mediterranean climate favorable for high-value vegetable production year-round (Griffin and White 1955). In California, several types of lettuce (*Lactuca sativa*) are gown on ∼32,389 ha, other common vegetables in coastal California include carrot (*Daucus carota*) grown on ∼25,100 ha, broccoli (*Brassica oleracea*) grown on ∼48,580 ha, and spinach (*Spinacia oleracea*) grown on ∼16,316 ha (Griffin and White 1955; Tourte et al. 2019). Farmers have traditionally used hand weeding as part of their weed control program, but labor costs are increasing, and labor is in short supply. Hand weeding costs are increasing, partly because of California legislation in 2016 that increased the minimum wage by a $1.00 per year until it reaches $15.00 in 2022 (Tourte et al. 2019). Weed removal is a time-sensitive activity and weeds must be removed early in the production cycle to prevent damage to the crop from weed competition, but workers are not always available when needed for weeding. Cultivators are another weed control component, but traditional interrow cultivators cannot remove weeds close to the crop. The difficulty of removing weeds close to the crop is why hand weeding is a necessary operation (Odero 2013). Weed management in organic vegetables is even more difficult than in conventional fields because of the lack of herbicides and high weed densities in organic fields. Organic producers have few effective weed control tools and new weed control options are needed (Fennimore et al. 2001). It is essential to use physical, cultural, and chemical control practices to develop an integrated pest management plan to avoid pest resistance and ensure effective weed and pathogen control (Fennimore et al. 2010). Current circumstances, such as increased hand weeding costs and lack of selective organic herbicides, threaten profitability; therefore, there is a need for additional pest control options (Odero 2013). The agricultural industry will suffer due to increasing costs in labor-intensive crop systems (Tourte et al. 2019). Crop and weed competition are a constant struggle, and the crop needs to be protected from weeds and the earlier weed removal is performed, the less likely weed competition will damage the crop (Bond et al. 1998).

Steam pasteurization of soil was developed in the late 19th century. Steam injected into the soil can control soil pathogens, insects, and weed seeds (Newhall 1955). Steam soil pasteurization is a physical method of soil disinfestation that controls pathogens like *Pythium* spp. and *Sclerotinia minor* (Runia and Molendijk 2010). Traditional methods like sheet steaming applied steam to the entire soil profile, which results in high fuel consumption (Langedijk 1959). Banded steam placement was found to be more efficient than broadcast sheet steaming (Langedijk 1959). Band steamers were developed to target steam into narrow strips of the soil carefully positioned where the seedline would be located after steam application to reduce costs and improve efficiency (Pinel et al. 2000). Mobile band steaming may be the best alternative to fumigants for pest control in the seedline (Baker 1962; Luvisi et al. 2008). Mobile band steamers were used commercially in Sweden treating 10 cm wide and 5 cm deep bands before planting sugar beet (*Beta vulgaris*) at a speed of 0.25 kph, resulting in a treatment rate of 18 $h{\cdot}ha^{-1}$ (Ascard et al. 2007). This treatment provided 90% weed control while consuming 570 1 ha^{-1} of diesel fuel. Hand weeding in the steam treatment was 49 $h{\cdot}ha^{-1}$ and in the control treatment 132 $h{\cdot}ha^{-1}$. Band steaming caused no adverse effects on beneficial microbial activity in organic field soils (Elsgaard et al. 2010).

Based on experience of previous work with steam application in strawberry, we designed and built a band steam applicator for vegetable crops (Fennimore et al. 2014). Steam band applicators worked well in suppressing weeds and soilborne pathogens in strawberries; therefore, we hypothesized that it could control weeds and pathogens in vegetable production. The objectives of this project were to evaluate pathogen and weed

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control efficacy of steam applied in a band before planting vegetables as well as the impact on crop growth and yield.

Materials and Methods

Four lettuce trials and one trial each of spinach and carrot were conducted with three different steam applicators during 2020 and 2021. Except for the spinach trial, all trials used a band steam applicator and were treated the same way targeting dwell times in the soil of 20 min from 60 to 70 °C to control soil pathogens and weeds effectively (Kim et al. 2021). Lettuce trials 1 and 2 were performed using a fabricated bed shaper steamer equipped with four sequential shanks injected steam in a band, 10 cm wide by 7 cm deep, connected to a 20 BHP steam generator (Sioux, Beresford, SD) used to supply steam at 0.6 bars centered on where the lettuce seed line was to be located on the raised beds (Fig. 1). The fabricated steam implement was towed by a 5520 John Deere tractor that was set at a constant 2,000 RPM, moving 2.4 m per minute while steaming. In spinach trial 3, steam was applied with a self-propelled steam applicator called the Steamy equipped with a compact diesel-fueled steam generator and applicator (JSE, Daegu, Republic of Korea; Fig. 2). Steamy was designed to treat flat ground only with 20 straight shanks, so raised beds were not used in this trial. In addition, the applicator physically mixed the steam with the soil as it passed through the plots.

Lettuce trials 4 and 6, and carrot trial 5 were treated with a steam applicator developed by the University of Arizona (UAZ). The UAZ steam applicator was equipped with a 550 $kg \cdot h^{-1}$ Clayton Sigma fire SF35 (Clayton Industries, City of Industry, CA) generator attached to a bed shaper and shanks that injected steam in a band, 10 cm deep by 10 cm wide aligned with where the crop seed line was to be located on the raised beds (Fig. 3).

Steam trials. The site location for trials 1 to 5 was at the University of California Agriculture and Natural Resources (UC ANR) Hartnell research station in Salinas, CA, 36°40′ 10.0399 N; 121°36′ 19.9784 W. The soil was a loam consisting of 53% sand, 32% silt, and 15% clay and with 2.09% organic matter. The electric conductivity of the soil is 1.65 dS/m with a pH of 7.03. Lettuce trial 6 was conducted at the Yuma Agricultural Center in Yuma, AZ. Critical trial events and dates can be found in (Table 1). Soil samples were collected before and after steaming to measure treatment effects on *Pythium* spp. colonies and *S. minor* sclerotia (i.e., lettuce drop, in all five trials at the UC ANR Hartnell station) (Table 1). Soil samples were assessed for propagules of *Pythium* spp. using a soil plating method. In addition, *S. minor* sclerotia densities were determined using a floatation method. Lettuce drop assessments in trial 6 were based on percentage of infested plants, but *Pythium* spp. assessments were not conducted in that trial. HOBO temperature recorders (T-Type thermocouples, U12 Outdoor; Onset Computer Corp., Pocasset, MA) were used to monitor soil temperatures at a depth of 10 cm during the steaming process and left in the soil for 24 h after steaming in trials 1 to 5. Tekcoplus data loggers were placed in the center of the seedline after steaming and the temperature was tracked every minute in trial 6 at Yuma, AZ.

Fig. 1. The fabricated bed shaper used as a steam applicator used in lettuce trials 1 and 2.

Treatments included in all trials were band steam and a no steam control and the trial design in all trials was a randomized complete block design with four replicates. The exception was spinach trial 3 where treatments were replicated six times. Plot sizes in lettuce trials 1 and 2 were 1 m wide by 32 m long. Lettuce trial 1 was steamed on 1 Jul 2020 and planted the next day (Table 1). Lettuce trial 2 was steamed on 21 Jul 2020 and planted a day later (Table 1). Both trials were planted with a Stanhay belt planter that used 5 cm in-line seed spacing. Data recorded in trials 1 to 5 were weed densities by species, disease incidence by plot, temperature, time of hand weeding, lettuce diameters, and crop yield.

In spinach trial 3, each plot was 1.5-m wide by 6.2-m long. The spinach Merrak Rz F1 cultivar was planted 2 days after treatment (DAT) on 28 Oct 2020 using a high-density, 8-line, 1-m-wide seeder (Table 1).

Lettuce trial 4 plots were 1-m-wide beds by 54.8 m long and steamed 7 Jul 2021. Lettuce cultivar Green Towers was seeded on 12 Jul 2021 (Table 1). Carrot trial 5 plots were a single 1-m-wide bed by 36.5 m long and steamed on 8 Jul 2021. Carrot cultivar Morelia was seeded 1 DAT on 9 July 2021 (Table 1). Trials 4 and 5 were planted with a Stanhay belt planter that used 5 cm in-line seed spacing for two seed lines for the lettuce trial and scatter shoe for the carrot trial that seeded two bands of 7.6 cm wide per bed.

Lettuce trial 6 plots were 1.06 m wide by 7.6 m long and the soil was a Holtville Clay. Steam was applied with the UAZ steam applicator at a speed of 0.24 kph on 16 Dec 2020. Lettuce cultivar Copper, an iceberg lettuce, was planted the next day (Table 1). Data recorded were stand counts, weed counts, diseased plant counts, and crop yield.

Pathogen soil assays. Before and after steaming soil was collected from the top 15 cm of the soil with a garden trowel to measure the abundance of *Pythium* spp. colonies and *S. minor* sclerotia residing in the soil. For *Pythium* spp., 2300 g of soil were randomly collected from each plot before and after steam application and placed into a paper bag for all trials except lettuce trial 6. *Pythium* spp. assays were conducted as follows: 1 g of soil with 15 mL of distilled water was plated onto five petri dishes that contained Difo Corn Meal Agar and replicated three times per plot for a total of 15 plates per

Fig. 2. The Steamy steam applicator from JSE, Republic of Korea, used in spinach trial 3.

Fig. 3. University of Arizona steam applicator used in carrot trial 5 and lettuce trials 4 and 6.

plot (Klose et al. 2008; Martin 1992). Petri dishes were stored in a dark room at 21 to 24 °C degrees and read after 24 and 48 h (Klose et al. 2008; Martin 1992).

Soil samples of 300 g were collected to measure the abundance of *S. minor* sclerotia in soils from trials 1 to 5, before and after steaming, then 100 g of soil from the samples was sieved through a 300-mm and 2-mm sieve (Subbarao et al. 1994). The remaining soil was put in an Erlenmeyer flask and 100 mL of 2% sodium hexametaphosphate (Calgon) solution was added. After 5 min in the solution, 1 L of tap water was added and then poured into a coffee filter paper. Sclerotia colonies on the filter paper were then counted under a microscope.

In lettuce trial 6, plots were inoculated with the isolate *Sclerotinia sclerotiorum. S. sclerotiorum* was grown at UAZ's Yuma Agricultural Center, Yuma, AZ, in Aug 2020 inside containers that contained barley seeds and mycelia of the pathogen. The *Sclerotinia* was allowed to grow for 4 to 5 weeks in an incubator at 18 °C. Plots were inoculated, 1 d before steaming by spreading *S. sclerotiorum* sclerotia on the bed tops at a rate of 3 g per 7.6 m and lightly raked. Disease incidence was recorded based on visual symptoms of the lettuce assessed periodically during the growing season and at harvest.

Weed densities. Weed density counts were collected by species, 1 and 2 weeks after treatment in two 460-cm^2 sample areas aligned with the steam band area for trials 1 to 5. Carrot trial 5 and lettuce trial 6 weed densities were measured at only at 1 week after treatment. In trials 1 to 5, weed control was recorded as percent reduction of the most common species relative to the no steam control. Lettuce trial 6 weed data were recorded based on total weed densities across species only. Weeds were counted and collected in all plots in spinach trial 3 at harvest.

Diseased plant counts. Lettuce plant stand evaluations were conducted by counting the number of healthy and diseased plants in 32 m of bed in lettuce trials 1 and 2. For spinach trial 3, the number of healthy and diseased spinach leaves in 1.5 m of bed were measured. For lettuce trial 4, the number of healthy and diseased lettuce leaves were measured in 9.1 m of bed and for trial 5, the number of healthy and diseased carrot tops were measured in 1.5 m of bed.

Measurement of hand weeding time. Time to hand weed a 3-m section of lettuce bed and 1.5-m section of spinach plot by a laborer was measured 1 and 2 weeks after steaming in trials 1 to 4. For carrot trial 5, timed weeding was performed on 1.5 m of bed. For lettuce trial 6, time weeding was measured in 7.5 m of bed ~1 week after cultivation.

Harvest. For all lettuce trials, the weight, size, and number of marketable heads were collected per 3 m of bed at harvest. For the spinach trial, 0.6 m (eight seed lines) of marketable spinach leaves was harvested and weighed. For carrot trial 5, the weight, diameter, and number of marketable mature carrots were collected per 1.5 m of bed at harvest. For lettuce trial 6, the head weight and yield were collected per 7.6 m of bed at harvest.

Crop canopy. Crop canopy diameters were measured at 41 d after planting for lettuce trials 1, 2, and 4. Crop diameters of 20 plants per plot were measured from the outermost leaf from one side to the outermost leaf on the other side with the ruler on the soil surface of the lettuce plant.

Statistics. Analysis of variance (ANOVA) and mean separation with least significant differences were performed using R Studio (R Studio, Boston, MA) and Agricultural Research Manager (Gyllings Data Management, Brookings, SD). The Levene's test of homogeneity of variance, ANOVA, and mean separation using Fisher's Protected LSDs were performed in R Studio at a significance level of $P = 0.05$. Data from trial 6 were subjected to ANOVA and mean separation was performed using Duncan's New Multiple Range Test at a significance level of $P = 0.05$.

Economic analysis. Treatment costs were calculated for the three romaine lettuce trials using trial data, information on the design and purchase of the steam machine, and information on the cost of labor and fuel. Gross revenues were computed using trial

Table 1. Critical dates for all trials done in Salinas, CA, and Yuma, AZ.

Trial/Crop	Steam model	Preplant/Steam/Pre soil collection	Planting/Post soil collection	Weed density measurements	Yield evaluations
1. Lettuce	Fabricated Bed Shaper	1 Jul 2020	2 Jul 2020	13, 27 Jul 2020	31 Aug 2020
2. Lettuce	Fabricated Bed Shaper	21 Jul 2020	22 Jul 2020	6, 24 Aug 2020	25 Sep 2020
3. Spinach	Steamy	26 Oct 2020	27 Oct 2020	6, 13 Nov 2020	13 Jan 2021
4. Lettuce	UAZ Applicator	7 Jul 2021	12 Jul 2021	26 Jul, 9 Aug 2021	22 Sep 2021
5. Carrot	UAZ Applicator	8 Jul 2021	9 Jul 2021	26 Jul 2021	1 Oct 2021
6. Lettuce	UAZ Applicator	16 Dec 2020	17 Dec 2020	29 Jan 2021	13 Apr 2021

Table 2. Total weed densities from five vegetable trials at Salinas, CA, 1 and 2 weeks after steam application.[i]

	Total weed densities				
	Lettuce trial 1	Lettuce trial 2	Spinach trial 3	Carrot trial 4	Lettuce trial 5[ii]
Treatments	(No. $100 \cdot cm^{-2}$)				
Steam only	2.3 b	3.2 b	5.9 b	0 b	0.1 b
Control	23.6 a	9.3 a	52.1 a	8.4 a	29.8 a
P value	0.0372	0.0213	0.0280	0.0044	0.0142

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.
[ii] Trial 5 had only one assessment.

Table 3. Time of hand weeding in hours per hectare (h/ha) in five vegetable trials 1 and 2 weeks after steam application.[i]

	Hand weeding time				
	Lettuce trial 1	Lettuce trial 2	Spinach trial 3	Lettuce trial 4	Carrot trial 5
Treatment	h/ha				
Steam only	163.0	123.5 b	22.72 b	24.20 b	63.23 b
Control	212.4	190.19 a	122.26 a	291.21 a	322.58 a
P value	0.1223	0.0390	0.0001	0.0080	0.0025

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 4. Iceberg lettuce yield and *Sclerotinia sclerotiorum*–infected plants in Trial 6 conducted at Yuma, AZ, in 2020.[i]

Treatment	Weed densities	Hand weeding time	Marketable yield	Infected plants
	Number/ha	h/ha	t/ha	%
Steam	3.702 b	3.23 b	39.702 a	1.0 b
Control	34.903 a	4.45 a	32.808 b	3.9 a

[i] Means within columns followed by the same letter are not significantly different according to Duncan's New Multiple Range Test ($P = 0.05$).

yield data and prices for romaine heads obtained from the U.S. Department of Agriculture (USDA) Agricultural Marketing Service.

Results

Soil temperature duration >70 °C at a depth of 10 cm for trials 1 to 5 was as follows: 1, 88 min; 2, 67 min; 3, 176 min; 4, 98 min; 5, 105 min. The no steam control soil temperatures were less than 40 °C in all trials. Weed densities in the steam-treated bands were 65% to 100% lower than the no steam control in trials 1 to 5 (Table 2). Steam reduced hand weeding time from 23% to 91% compared with the no steam control in all trials (Table 3). In trial 6, nettleleaf goosefoot, common lambsquarters (*Chenopodium album*), California bur clover (*Medicago polymorpha*), and little seed canary grass (*Phalaris minor*) were the dominant weeds present, and steam provided 89.4% control relative to the no steam control (Table 4). The steam treatment in lettuce trial 1 reduced hairy nightshade (*Solanum physalifolium*) by 91%, shepherd's-purse (*Capsella bursa-pastoris*) by 80%, little mallow (*Malva parviflora*) by 96%, and burning nettle (*Urtica urens*) by 80% (Table 5). In lettuce trial 2, the steam treatment reduced hairy nightshade by 64%, shepherd's-purse by 94%, little mallow by 84%, and burning nettle by 84% (Table 6). Steam treatment in spinach trial 3 reduced hairy nightshade by 93%, shepherd's-purse by 81%, burning nettle by 89%, and annual bluegrass (*Poa annua*) by 96% (Table 7). In lettuce trial 4, the steam treatment reduced hairy nightshade, shepherd's-purse, and nettleleaf goosefoot (*Chenopodium murale*) all by 100% (Table 8). In carrot trial 5,

Table 5. Reduction in weed densities by species compared with the control: lettuce trial 1.[i]

	Hairy nightshade	Little mallow	Shepherd's-purse
Treatments	Reduction %		
Steam only	91 b	96	80 b
Control	0 a	0	0 a
P value	0.0129	0.1053	0.0002

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 6. Reduction in weed densities by species compared with the control: lettuce trial 2.[i]

	Hairy nightshade	Little mallow	Shepherd's-purse	Burning nettle
Treatments	Reduction %			
Steam only	64	84	94 b	84 b
Control	0	0	0 a	0 a
P value	0.2077	0.6210	0.0219	0.0011

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 7. Reduction in weed densities by species compared with the control: spinach trial 3.[i]

	Hairy nightshade	Annual blue grass	Shepherd's-purse	Burning nettle
Treatments	Reduction %			
Steam only	93 b	96 b	81 b	89 b
Control	0 a	0 a	0 a	0 a
P value	0.0372	0.0035	0.0103	0.0282

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 8. Reduction in weed densities by species compared with the control: lettuce trial 4.[i]

	Hairy nightshade	Nettleleaf goosefoot	Shepherd's-purse
Treatments	Reduction %		
Steam only	100 b	100 b	100 b
Control	0 a	0 a	0 a
P value	0.0184	0.0471	0.0005

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 9. Reduction in weed densities by species compared with the control: carrot trial 5.[i]

Treatments	Hairy nightshade	Common purslane	Burning nettle
	Reduction %		
Steam only	97	97 b	97 b
Control	0	0 a	0 a
P value	0.1683	0.0124	0.0054

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 10. Abundance of *Pythium* spp. colonies in the seedline before and after steam application for lettuce trials 1 and 2.[i]

	Lettuce trial 1			Lettuce trial 2		
	Pretreatment	Posttreatment		Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %	Propagules/g (ppg soil)		Reduction %
Steam only	23.1	11.6 b	50.0	34.1	3.7 b	89.0
Control	25.1	24.0 a	4.5	38.7	32.1 a	17.2
P value	0.6700	0.0002		0.0583	0.0002	

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 11. Abundance of *Pythium* spp. colonies before and after treatment for spinach trial 3.[i]

	Spinach trial 3		
	Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %
Steam only	10.5	0.7 b	93.0
Control	12.1	10.4 a	13.6
P value	0.4498	0.001	

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 12. Abundance of *Pythium* spp. colonies before and after treatment for lettuce trial 4 and carrot trial 5.[i]

	Lettuce trial 4			Carrot trial 5		
	Pretreatment	Posttreatment		Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %	Propagules/g (ppg soil)		Reduction %
Steam only	24.6	0.02 b	99.9	22.2	0.9 b	95.6
Control	27.4	25.7 a	4.5	19.1	18.6 a	2.5
P value	0.0320	0.0001		0.7509	0.0006	

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 13. Abundance of sclerotia in soil before and after treatment for lettuce trials 1 and 2.

	Lettuce trial 1			Lettuce trial 2		
	Pretreatment	Posttreatment		Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %	Propagules/g (ppg soil)		Reduction %
Steam only	5.6	1.2	77.2	5.8	0.8	85.1
Control	4.5	4.3	2.8	6.8	7.3	–7.2
P value	0.4842	0.2539		0.652	0.1379	

Table 14. Abundance of sclerotia in soil before and after treatment for spinach trial 3.[i]

	Spinach trial 3		
	Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %
Steam only	4.7	0.2 a	94.7
Control	4.9	7.5 b	–52.7
P value	0.6911	0.0002	

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

the steam treatment reduced hairy nightshade, common purslane (*Portulaca oleracea*), and burning nettle all by 97% relative to the no steam control (Table 9).

The abundance of *Pythium* colonies in the steam treatment in lettuce trial 1 was reduced by 50% compared with the no steam control (Table 10). In trials 2 to 5, the abundance of *Pythium* spp. colonies in the steam treatment was reduced by 89% to 100% compared with the no steam control (Tables 10–12).

Posttreatment soil samples indicated that steam reduced lettuce drop sclerotia by 69.1% to 94.7% relative to the no steam control in trials 1 to 5 (Tables 13–16). The steam treatment in lettuce trial 6 reduced *S. sclerotiorum*–infested plants by 74% compared with the no steam control (Table 4). In lettuce trials 2 and 4, steam treatment reduced lettuce drop incidence 67% to 70% compared with the no steam control (Table 17). Lettuce trial 4 had the highest disease pressure, and this explains why this trial had greater lettuce yields in the steam-treated soils (Tables 17 and 18).

In lettuce trials 1 and 4, yields were 22% and 28% higher in the steam-treated soils than the no steam control (Table 18). In lettuce trial 6, yields were 17% higher in the steamed treatment than the nontreated control likely due to control of lettuce drop (Table 4). There were no treatment effects in the other trials and is likely due to varying disease pressure among the other trials (Table 18).

The lettuce diameters in the steamed soil in trials 1, 2, and 4 were 14%, 10%, and 24% larger, respectively, than the no steam controls (Table 19). Carrot diameters were 10% larger in steamed soil than the no steam control (Table 19).

Economic analysis. The economic analysis considers the operational costs of a prototype steam applicator that was built by UAZ and tested in Salinas, CA. The Clayton Sigma Fire SF35 steam generator was purchased from Clayton Industries for $80,051. The custom bed shaper sled was built in Yuma, AZ, at Keithly-Williams Fabrication for $25,000. The total annual steam applicator operating cost is $266,743 with an equipment life of 5 years. Machine operation for 9 h per day would allow the applicator to treat 268 ha per year. Additional operation and capital costs can be found in Table 20.

Revenue for romaine lettuce. The daily romaine lettuce prices were obtained by averaging daily price calculated as the daily low and high prices using the Agriculture Marketing Service website, 2020 Salinas-Watsonville District (USDA 2020). The price for organic romaine was $30.32/box and the conventional romaine was $27.20/box. A. Spalding (unpublished data) used a harvest cost of $0.26/kg for romaine head of lettuce (Table 21). The weight per box was obtained from Graham Hunting of the Monterey County Agricultural Commissioner's Office (Table 21). The conventional and organic gross revenue for the lettuce trials were calculated using yields from the trial and head prices to obtain head

Table 15. Abundance of sclerotia in soil before and after treatment for lettuce trial 4.

	Lettuce trial 4		
	Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %
Steam only	3.1	0.8	72.1
Control	2.6	2.3	9.5
P value	0.4517	0.4610	

Table 16. Abundance of sclerotia in soil before and after treatment for carrot trial 5.

	Carrot trial 5		
	Pretreatment	Posttreatment	
Treatment	Propagules/g (ppg soil)		Reduction %
Steam only	1.6	0.5	69.1
Control	2.3	1.8	21.0
P value	0.5403	0.0631	

Table 17. Number of plants infected with lettuce drop at harvest.[i]

	Crop stand (diseased)		
	Lettuce trial 1	Lettuce trial 2	Lettuce trial 4
Treatment	No. (1000/ha)		
Steam only	1.97	4.94 b	11.85 a
Control	4.94	14.82 a	39.02 b
P value	0.1411	0.0023	0.0009

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 18. Marketable yields presented as fresh weights from five vegetable trials.[i]

	Marketable yield				
	Lettuce trial 1	Lettuce trial 2	Spinach trial 3	Lettuce trial 4	Carrot trial 5
Treatment	Tons/ha				
Steam only	81.75 a	59.03	32.85	104.48 a	65.70
Control	63.72 b	52.85	32.11	75.08 b	58.29
P value	0.0068	0.1476	0.8171	0.0347	0.0955

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 19. Lettuce plant diameters and carrot root diameters at harvest.[i]

	Plant diameters			
	Lettuce trial 1	Lettuce trial 2	Lettuce trial 4	Carrot trial 5
Treatment	mm/plant		mm/carrot	
Steam only	853.4 a	657.8 a	820.4 a	728.98 a
Control	736.6 b	591.8 b	627.3 b	657.86 b
P value	0.0050	0.0436	0.0116	0.0456

[i] Mean separation by Fisher's Protected LSDs. Means followed by the same letter within columns do not differ significantly at 5% level.

Table 20. Operating and capital costs for steam applicator based only on the University of Arizona steamer.

Hours/ha	22.4
Treatment/ha	111.6
Treatment days per year	278
Hours per treatment days	9
Labor cost, $/ha	972.71
Fuel cost, $/ha	1,112.44
Machine cost, $/ha	305.02
Cost of field operation, $/ha	2,390.17
Total annual steam applicator operation cost, $	266,742.97

price per kg (Table 21). The gross revenue per ha for steam and the control was calculated by obtaining the yields and the area of the plots (Table 22). Gross revenue for the steam-treated lettuce in trial 4 had the highest revenue of $11,480.56/ha compared with $8249.80/ha for the no steam control (Table 22). In trial 1, the steamed treatment gross was $3939.65/ha and $2675.01/ha for the no steam control (Table 22). In trial 2, the steamed treatment gross revenue was $2842.97/ha and $2546.57/ha for the no steam control (Table 22).

Table 21. Organic romaine harvest cost, box weight prices.

Harvest cost, $/kg	0.26
Organic romaine heads price, $/kg	2.60
Daily price of organic, $/box	30.32
Weight of box, kg/box	11.3

Discussion

Management of weeds for most high-value vegetable production systems is challenged by a lack of herbicides and a shortage of labor for hand weeding. Soil disinfestation with steam to control pathogens and weed seed in the soil may be a way to supplement the pest control needs of vegetable growers. Traditional steam pasteurization techniques have long used stationary methods of soil steaming in greenhouse production, but those methods are not suitable for open field use (Melander et al. 2005). Melander et al. (2005) and Pinel et al. (1999) suggested the need for a mobile band steam application method that may provide an effective alternative to soil fumigants. Steam pasteurization of soil may be viable for organic farmers who have few pest management tools, or conventional farmers who need to treat buffer zones in their fields where fumigants may not be applied. We learned that the ability to adjust the speed of application to control the soil temperature was an advantage because it was possible to avoid over application of steam, which results in excessive fuel use and can damage beneficial soil organisms. We evaluated three steam applicators, two of which were commercial models that worked well in-field production sites. However, there is a need for improvements to consider in terms of ease of use, fuel efficiency, and flexibility to adjust to varying field soil types and cropping systems. Steam was injected into the soil with a target temperature of 70 °C, which was accomplished and maintained for a 20-min dwell time in all trials. Soil temperature results gathered after steam application in the field were similar to other mobile steamer applicator studies (Carlesi et al. 2021; Kim et al. 2021; Melander et al. 2005; Pinel et al. 1999).

The premise of this research was to evaluate the pest control efficiency of steam applied in a band before planting. We found that weeds, pathogens, and hand weeding times were reduced in steam-treated plots, and yields improved part of the time. Soil temperatures were above 70 °C in trial 3, for 176 min, using the Steamy equipped with a rototiller that mixed steam with the soil. Mixing the soil as the steam was incorporated in the soil allowed for better steam penetration targeting soil aggregates compared with trials 4 and 5 done by the UAZ steamer. The UAZ steamer maintained soil temperatures above 70 °C for 98 to 105 min. The UAZ steamer has a bed shaper attached to it to ensure the planting surface on the raised beds stays firm after application.

The weed data indicate that steam disinfestation does an excellent job controlling weeds, especially on hairy nightshade, nettleleaf goosefoot, shepherd's-purse, burning nettle, and common purslane. Because trials 1 to 5 were dependent on resident pathogen

Table 22. Organic gross revenue for three lettuce trials only.

	Lettuce trial gross revenues		
	Lettuce trial 1	Lettuce trial 2	Lettuce trial 4
Steam yield, t/ha	81.79	59.05	104.52
Control yield, t/ha	63.75	52.88	75.10
Organic head price, $/kg	2.60	2.60	2.60
Gross revenue steam, $/box	40.14	28.92	51.18
Gross revenue control, $/box	31.29	25.89	36.78
Gross steam revenue, $/ha	3,939.65	2,842.97	11,480.56
Gross control revenue, $/ha	2,675.01	2,546.57	8,249.80

populations in the trial blocks, there was variability in disease pressure among trials. Steam reduced *S. minor* sclerotia by 69% to 95% compared with the no steam control, a similar result to other studies (Pinel et al. 2000; Triolo et al. 2004). Lettuce trial 6 found that the steam treatment reduced *S. sclerotiorum*–infected plants from 3.9% in the no steam control compared with 1% in steam treatment (Table 4). In addition, the steam treatment in trials 2 to 5 reduced *Pythium* spp. colonies by 89% to 100% compared with the no steam control, similar to what others have found (Pinel et al. 2000). Of all the trials, lettuce trial 4 had the highest incidence of diseased lettuce plants and the best control of *Pythium* wilt colonies. The lettuce diameter size for the steam-treated lettuce was 13% to 24% larger in lettuce trials 1 and 4 with an increase in yield when comparing it with the no steam control in the rest of the trials, which suggests that pathogens were suppressed (Tables 18 and 19).

The increases in yields and corresponding increases in gross revenues for the lettuce trials in this research show the potential for steam to not only cover its costs, but to increase net revenues. A steam study done in strawberry production by Michuda et al. (2021) suggested a maximum soil temperature of 62 to 63 °C should be a standard for growers at a duration of 41 to 44 mins to maximize net returns and increase fruit yield. In our lettuce steam study, we surpassed that reaching temperatures above 70 °C, which increased yield and gross revenue per acre. Better disease control resulted in greater lettuce growth with a gross revenue of $11,480.56/ha averaged across all trials for the steam-treated lettuce vs. $8249.80/ha for the nontreated control lettuce, a difference of $3230.76/ha (Table 22). The cost of field operation is $2398.39/ha, which is feasible to use in-field commercially given the value of vegetable crops. In addition, we project that there is room to reduce this cost with greater application efficiencies through insulation and improved injector design.

However, the UAZ steamer needs further machine development. Research and development should focus on the implementation of a method to mix steam with the soil for better distribution. Currently, it takes 22.4 h to steam a hectare (Table 20). If application time can be reduced, then the amount of fuel costs per hectare can be reduced proportionally. These results indicate that with a greater reduction of pathogen inoculum and weed seeds in the soil using steam, this will allow more opportunity for the crop to thrive with less pest competition. This work shows the potential that band steaming has on field weed and pathogen control as stated by Carlesi et al. (2021).

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