Economic Viability of Steam as an Alternative to Preplant Soil Fumigation in California Strawberry Production

Yan Xu, Rachael E. Goodhue^{1,2}, and James A. Chalfant¹

Department of Agricultural and Resource Economics, University of California, Davis, One Shields Avenue, Davis, CA 95616

Thomas Miller and Steven A. Fennimore

Department of Plant Sciences, University of California, Davis, 1636 East Alisal Street, Salinas, CA 93905

Additional index words. Monte Carlo techniques, soil disinfestation, pesticide use regulations, buffer zone regulations, economics of agricultural systems, mustard seed meal soil amendment

Abstract. One challenge of conducting research regarding agricultural production systems is that field trials are time consuming and expensive, limiting their scale and scope. Thus, policymakers and producers benefit from researchers extracting as much information as possible from each trial. We used the Monte Carlo techniques and the sensitivity analyses to enhance our analysis of the competitiveness of steam as an alternative to fumigation for preplant soil disinfestation in California strawberry production. Chloropicrin + 1,3-dichloropropene 59.6:39 (CP + 1,3-D) resulted in higher mean net returns than did steam. However, the Monte Carlo analysis showed that in one field trial there was a high probability that steam would be more profitable, whereas in the other it was quite unlikely. We also assessed the change in economic performance of steam when it was applied combined with soil amendments of mustard seed meal (MSM). Switching from steam to steam + MSM would have reduced mean net returns. The Monte Carlo results showed that steam + MSM performed at least as well as steam alone around half the time. We evaluated factors that were likely to affect the net returns, defined as total returns minus treatment, weeding, and harvest labor costs, of using steam in the near future. Reductions in application time increased net returns. A decrease in the price of propane increased net returns.

Today, California growers face an increasing number of requirements regarding the preplant application of soil fumigants promulgated by federal, state, and county governments. These requirements are issued as label requirements, use regulations, and county permit conditions. Because of increasing regulation of fumigants, it is unclear that their use as the exclusive means of soil disinfestation will continue to be economically viable, even if they remain technically available for growers to use on some land. Some regulations prohibit fumigant applications entirely, such as buffer zone distance requirements for applications near sensitive sites, such as schools (California Department Pesticide Regulation, 2015a). The efficacy and economic feasibility of a nonfumigant treatment is an important consideration

when part of a field cannot be fumigated. Leaving buffer zones untreated reduces yields and provides a reservoir for pests and disease, which can spread into treated areas of the field. Soil disinfestation using steam is one non-chemical alternative that can be used where the preplant application of soil fumigants is prohibited.

Steam has demonstrated efficacy against weed, insect, nematode, and pathogenic pests affecting crops (Fennimore et al., 2014). It has been used for decades as part of greenhouse floriculture production. In addition to its technical efficacy, the application of steam is safer than applications of chemical fumigants for human health, and no buffer zones are required. Thus, even if the majority of a field is treated with a fumigant, steam can increase field-level returns by reducing weed and pest pressure if it is used in the field's buffer zone.

This analysis evaluates the economic feasibility of steam application as a mean of soil disinfestation before planting for strawberries produced in California's Central Coast production region. It compares the economic performance of steam to that of CP + 1,3-D and an untreated control. Using results from a separate trial, it compares the economic performance of steam when it is applied alone to when it is paired with soil amendments of MSM and an untreated control.

The economic feasibility of a technology is dependent on the crop or cropping system. One consideration in the production system we examine is that transitioning to alternative crops is challenging. Cropland values are quite high in strawberry production areas on California's Central Coast compared with cropland values in the Central Valley, and growers who produce strawberries are specialized in berry production (An et al., 2009); berry growers' desire to control their cropland is a primary driver of cropland values in the region (American Society of Farm Managers and Rural Appraisers-California Chapter, 2015). Thus, identifying technically and economically viable alternatives for preplant soil fumigation in California strawberry production is an urgent task for researchers.

Strawberries are an economically important crop in California. In 2012, the total value of California strawberry production was US\$2.1 billion, ranking strawberries sixth among California commodities (California Department of Food and Agriculture, 2013). Strawberry production is a significant user of preplant soil fumigation in California. In 2012, it accounted for 75% of the total use of CP and 24% of the total use of 1,3-D (California Department of Pesticide Regulation, 2015b).

There has been relatively little economic analysis of the use of steam for preplant soil disinfestation in strawberry production. Various steam application technologies have been tested alone or in combination with other soil disinfestation techniques. Samtani et al. (2011) found that steam provided strawberry yields and weed control comparable to CP + 1,3-D but did not evaluate economic feasibility explicitly. Samtani et al. (2012) tested the efficacy of steam in soil pest control and whether soil disinfestation using both steam and solarization affected pest control and yield response, compared with application of these two alternatives individually. Treatments included methyl bromide: chloropicrin, solarization and steam, solarization alone, and steam alone. The treatments of steam alone and the combination of steam and solarization provided the most effective pest control, and had yield effects comparable to methyl bromide:chloropicrin. Regarding economic viability, the authors concluded that net returns from treatments of solarization or steam were lower than those from the methyl bromide:chloropicrin treatment.

Fennimore et al. (2013) evaluated the efficacy of the preplant application of anaerobic soil disinfestation (ASD) and steam with and without a MSM soil amendment for strawberries. Trial results suggested that steam with and without MSM had comparable weed control effects to CP + 1,3-D, whereas ASD was less effective than CP + 1,3-D. Both steam and ASD treatments had yields equivalent to CP + 1,3-D. However, the costs associated with steam application were much higher than those for CP + 1,3-D.

This paper provides an example of the use of economic analysis in multidisciplinary production system research projects. It is

Received for publication 1 Nov. 2016. Accepted for publication 9 Jan. 2017.

This analysis was conducted as part of Yan Xu fulfilling degree requirements for a Master's of Science in Agricultural and Resource Economics, supervised by Goodhue, Chalfant, and Fennimore. Funding for this study was from support awarded in USDA NIFA Methyl Bromide Transitions grants 2010-51102-21648 and 2013-51102-21524.

¹Member of the Giannini Foundation of Agricultural Economics, University of California.

²Corresponding author. E-mail: goodhue@primal.ucdavis.edu.

now expected by most granting agencies and stakeholders that such projects will include an analysis of economic feasibility of the examined techniques. Studies on alternative soil disinfestation techniques are limited due to costs and time involved in conducting the studies. Thus, policymakers and producers will benefit from researchers extracting as much information as possible from each trial. Growers are also concerned with the reliability of the performance of alternative treatments, which is not captured as part of a standard partial budget analysis.

The structure of the first set of trials we evaluated allowed us to apply techniques commonly used by economists to obtain more information than that provided by a standard partial budget analysis. We used Monte Carlo analyses to enhance the information regarding economic viability that can be obtained from the field trials. We compared the distributions of net returns, defined as total returns minus treatment, weeding, and harvest labor costs, using the observed variability in yield and weeding time across plots for each treatment. Evaluating the distributions provided a fuller picture of the net returns obtained from steam relative to those obtained from a conventional soil fumigant. The study also used sensitivity analysis to consider the effects of changes in the yield distribution, cost of propane, and steam application technology on the relative economic performances of the treatments.

Materials and Methods

Data. In the 2011–12 production season, there were two trial locations within California's Central Coast production region: one at the California Strawberry Commission research site at the Monterey Bay Academy (MBA) near Watsonville and one at the USDA/University of California research site (Spence) near Salinas. Trials followed the randomized complete block design, and included four replicates at the MBA site and five at the Spence site. Treatments included steam (target soil temperature of 70 °C for >30 min at 15 cm depth), CP + 1,3-D (392 kg·ha⁻¹ at the MBA site and 280 kg·ha⁻¹ at the Spence site), and an untreated control. In the 2012–13 production season, randomized complete block designs with four replications were applied in field trials at a commercial research field (TCR) near Watsonville. Treatments included steam (target soil temperature of 70 °C for >30 min at 15 cm depth), steam + MSM (incorporating 3360 kg·ha⁻¹ pelletized MSM before the steam treatment), and an untreated control. Fennimore et al. (2014) described the trials more fully. The yield and weeding time data were from field trials conducted in the 2011–12 and 2012–13 production seasons. Yield was recorded for each treatment in each trial by a commercial harvest crew once or twice a week as appropriate and converted to kilograms/hectare. The time to hand weed the length of each plot by a field worker was recorded for each treatment in each trial and converted to hours/hectare.

Using sites with different degrees of weed and disease pressure provided information on how these factors influence the technical and economic viability of steam. There were a number of differences between the two 2011–12 sites, including the number of treatment replicates, the CP + 1,3-D application rate, pre-existing weed seed banks and pathogen populations, and field management. Ex ante, because the Spence site had higher weed and disease pressure, we hypothesized it would have higher weeding time and lower yields. This hypothesis was supported for each of the three treatments (Fennimore et al., 2014). *t* tests were conducted to test for statistically significant differences in the mean values of both the yield and weeding time between the two sites for each of the three treatments in the 2011–12 trials (for this set of *t* tests, we assumed that the variances of both the yield and weeding time of each treatment would be different at the two sites. Under this assumption, the test results were distributed as a Student's *t* with *v* df, where *v* is given by Satterthwaite's formula (StataCorp, 2013). The results of the tests showed that the differences were statistically significant.

Another set of *t* tests (the assumptions provided in the previous set of *t* tests apply to these tests as well) was conducted to evaluate the difference in the mean values of both yield and weeding time at the same site across different treatments. In the 2011–12 production season, weeding times of all treatments were statistically significant different from each other at the MBA site. Regarding yield, only steam had a yield significantly higher than the untreated control. At the Spence site, steam and CP + 1,3-D were significantly higher in yield and weeding time than the untreated control. Results from the two treatments were not statistically different from each other. In the 2012–13 production season, steam and steam + MSM displayed no statistically significant differences in yield or weeding time. Steam and steam + MSM each had significantly higher yields and lower weeding times than the untreated control.

Economic data were compiled from multiple sources. Picking rates (flats/hour) and the sales commission rate were from the most recent University of California Cooperative Extension cost study for conventional strawberry production on the Central Coast (Bolda et al., 2010). Wage rates for Central Coast agricultural workers were obtained via a personal communication (Don Stewart, Staff Research Associate in the Department of Agricultural and Resource Economics at University of California, Davis, Dec. 2015). In addition to the necessary labor, harvest costs that were available for the seasons considered included, but were not limited to, cooling cost/flat, material cost/flat, the CSC assessment/flat, and the sales commission rate/flat. These costs were available in Bolda et al. (2010), but not for the seasons in question. The price of propane and costs for applying each treatment were obtained from the industry sources and the field trials.

Prices for fresh strawberries for the Salinas–Watsonville district shipping point were obtained from the U.S. Department of Agriculture's Agricultural Marketing Service (2015). The data were the average of low and high weekly prices for medium-large strawberries packed in eight 1-lb containers for the time period in which marketable strawberries were harvested in the trials. For the 2011–12 production season, marketable strawberries were harvested from Mar. 28 to Sept. 22. Because of the limited volumes, no shipping point price was reported from Mar. 28 to Apr. 21. We set the missing price value to the available price of the closest week that was the week end of Apr. 28. For the 2012–13 production season, marketable strawberries were harvested from Apr. 6 to Oct. 19. Because of the limited volumes, no shipping point strawberry price was reported for the week ending Apr. 6, and we set the missing price value to be equal to the price value of the week ending of Apr. 13. We then calculated the seasonal average of strawberry price of eight 1-lb containers by averaging the reported weekly prices for each production season.

Distribution of returns net of treatment, weeding, and harvest labor cost. We calculated returns net of treatment costs, weeding costs, and harvest labor costs for each plot-treatment-trial site combination to compare the returns of the different treatments. We excluded other costs for which data were not available for the production seasons examined. Apart from nonlabor harvest costs, these costs were constant across treatments. For brevity, we chose to refer to these returns as net returns. NR_{it} for each plot *i* of treatment *t* at each trial site were defined as

$$NR_{it} = P * (1 - c) * Y_{it} - TC_{it} - HC_{it} - WC_{it} \quad (1)$$

where *P* was the seasonal average price of strawberries, *c* was the selling commission rate (8% of total revenue), *Y_{it}* was the cumulative yield, *TC_{it}* was the treatment cost, *HC_{it}* was the harvest cost, and *WC_{it}* was the weeding cost.

For the purpose of simulating total revenue, we argued there was no additional value obtained by using weekly prices. This assessment was based on a statistical test. We conducted a two sample *t* test to test whether the difference in total revenues using seasonal and weekly price was statistically significant for each treatment and field site. For both the 2011–12 and 2012–13 production seasons, the *t* test results suggested that the difference in total revenues calculated using weekly prices and using the seasonal average price was statistically insignificant at the 1% significance level for each treatment at each location.

The computation of the treatment cost *TC_{it}* varied. For steam, *TC_{steam}* was calculated according to Eq. (2). It was the sum of fuel cost (*fc*), labor cost (*lc*), and the annualized cost of the steam applicator (*mc*). Fuel cost was the product of the fuel price and liters/treated

hectare. According to field trial records, propane price was US\$0.69 per liter and the liters/treated hectare equaled 10,951.02. Labor cost was the hourly wage plus benefits for the one field worker (\$11.88) and one operator (\$14.52) required for the applicator multiplied by the treatment time hour/hectare. According to field trial records, the treatment time hour/hectare was 38.3. For steam + MSM, $TC_{\text{steam} + \text{MSM}}$ was the sum of TC_{steam} and the per hectare treatment cost of MSM (\$2553.56/hectare). Labor hours, fuel cost, and the per hectare cost of MSM were obtained from the field trial. The annualized cost/treated hectare of the steam applicator was \$626.16 and it was constructed using manufacturing cost estimates obtained from a commercial manufacturer. This cost included annual depreciation and interest costs [see Boehlje and Eidman (1984) for a detailed explanation].

$$TC_{\text{steam}} = fc + lc + mc \quad (2)$$

For CP + 1,3-D, the treatment cost was the custom application cost of \$4694.95 per hectare. There was no treatment cost for the untreated control.

The harvest cost function HC_{it} was:

$$HC_{it} = Y_{it} * \left(\frac{l}{pr} + m + c + \text{CSC Assmt} \right) \quad (3)$$

where Y_{it} was the cumulative yield, l was the wage (\$11.88/hour) paid to workers for harvesting, pr was the picking rate (6 flats/hour of labor), m was the material cost (\$1.68/flat), c was the cooling cost (\$0.50/flat), and CSC Assmt was the assessment fee (\$0.0175/flat) paid to the California Strawberry Commission.

The weeding cost function WC_{it} was the product of weeding time (wt_{it}) and the wage which was \$11.88/hour:

$$WC_{it} = wt_{it} * \text{wage} \quad (4)$$

The only variables that varied across plots for the same treatment at a site were the cumulative yield and weeding time. We obtained the point estimate of net returns for each treatment using the mean cumulative yield (y) and weeding time (wt). We then computed the standard deviation of cumulative yield and weeding time for treatment t at site j and simulated the probability distribution of net returns assuming that these variables were normally distributed and statistically independent.

The economic literature regarding crop yield distributions has focused primarily on major crops, primarily corn, cotton, sorghum, soybean, and wheat. It has relied on highly aggregated panel data, so not all of its conclusions were applicable to the plot-level data collected in this study. Just and Weninger (1999) identified three methodological problems that tended to lead to type I errors when testing for the normality of crop yields. For our purposes, the relevant problem for our analysis was that aggregate data did not reflect farm-level data; our data were even more refined. Although Atwood et al. (2003) identified a source of type II errors, it

was how yields were detrended over time which was not relevant for our analysis. Harri et al. (2009) also found that how time trends were modeled was a key determinant of whether normality of the yield distribution was rejected. Hennessy (2009a, 2009b) provided theoretical reasons why crop yield distributions might not be normal. Gibbons and Ramsden (2005) could not reject the hypothesis that crop yields were distributed normally, and used this assumption to conduct a Monte Carlo simulation analysis to examine the robustness of recommending farm planning models to climate change.

Døving and Måge (2001) and Døving (2004) modeled site-level weather conditions and fungicide treatments as determinants of strawberry yields in Norway, but did not consider the distribution of yields; their assumption regarding the distribution of the error term in their regression model was not included in the article nor was the normality of the yield distribution tested. In ordinary least squares regression models, errors were assumed to have a normal distribution. Wu et al. (2015) estimated a yield distribution using state-level, weekly information for Florida. They used the generalized method of moments. The distribution of errors was asymptotically normal.

Monte Carlo analysis of only selected variables is an accepted approach for analyzing the robustness of study results to key determinants, including crop yields as in Gibbons and Ramsden (2005). López et al. (2014) used data on weather, accumulated yield and fruit on plant at different levels of maturity to predict strawberry yield using the Monte Carlo analysis. Limiting the number of variables aided in interpreting the results (Lien, 2003). The distribution of weeding time had not been addressed in the literature. For consistency with the yield distribution, we assumed that weeding time was distributed normally.

Using the normal distribution for each variable as suggested in the literature, we drew 500,000 random, independent observations of yield, and weeding time for each treatment. The corresponding value of net returns for each treatment for each draw was then calculated, providing a simulated probability distribution of net returns for each treatment at each site. For each observation, we compared net returns across treatments for each site and production season.

Sensitivity analysis: alternative distribution assumptions of yields. We conducted a sensitivity analysis to evaluate how changes in the specified yield distribution would have changed the net returns in both the 2011–12 and the 2012–13 trials. We used two alternative distributions for yields: a t distribution and a nonstandard beta distribution. For the t distribution, we used three alternative df (10, 20, and 30) to allow variations in the probabilities assigned to the observations in the tails. For the nonstandard beta distribution, we fixed the lower bound of the distribution at zero and set the upper bound to be either equal to the same as, or 110%, or

115%, respectively, of the highest cumulative yield in plot level observed for each treatment.

Sensitivity analysis: learning and adoption of new technology. We conducted a sensitivity analysis which varied the value of the steam application cost to evaluate how much the net returns in the 2011–12 trials changed (both of the treatments in 2012–13 used steam, so the sensitivity analysis was not applicable). Herein, we considered how the economic performance of steam relative to other preplant soil disinfestation methods changed in response to a change in the cost of a steam treatment. We addressed two factors: a planned scaling up of the application technology and predicted learning by doing, which would reduce application time and labor cost.

First, the steam applicator used in the trials treated one bed at a time. The commercial machine currently under development would treat two beds at once, thus capturing economies of scale. Although scaling up the applicator would not halve treatment times or fuel costs, it should lower both significantly. Second, learning by doing may reduce application costs as users improve efficiency by repeatedly using a technology. If a new technology used methods relatively similar to an existing technology, then relatively little learning may be required. The more novel the technology, the greater the potential need for operators to gain experiences in using it.

Economic research conducted in other industries has documented the effects of learning by doing on costs and productivity (e.g., Bahk and Gort, 1993; Hartley, 1965; Nakamura and Ohashi, 2008). During the field trials, the operators were still in the process of learning how to use the steam applicator. However, application times were reduced compared with previous trials conducted by the investigators. To the extent that steam applications are done by custom operators, rather than by growers, one would expect gains from learning by doing to be captured quickly due to the custom applicator's larger treated acreage. This suggested that there remained some scope for efficiency gains from improvements in skills of users over time.

Thus, findings of previous studies of technology and innovation, as well as information acquired outside the field trial itself regarding steam preplant soil disinfestation, suggested that the field trial results could understate the net returns of steam to commercial growers. Arguably, any assessment of potential future effects on application costs was arbitrary, at least to some extent. Recognizing this, we evaluated a range of potential reductions to capture the possibility of improvements while recognizing that the precise degree of efficiency gain remained uncertain. We used our experience-based assessment of these two factors' effect on application times to identify a relevant range of treatment times. On the basis of observations to date of steam

applications, knowledge regarding machinery operation for field applications more generally, and knowledge of planned technology improvements, we hypothesized that the future commercial steam applicator's treatment time A would be distributed uniformly within the range of 17.3 to 24.7 h·ha⁻¹:

$$A \sim U(17.3, 24.7) \quad (5)$$

We followed the same procedure for calculating net returns as in the base model, with the exception of replacing the fixed application time with a draw from the uniform distribution of application times specified in (3) for each observation.

Sensitivity analysis: propane price. Steam was an energy-intensive technology, and its cost was dependent on the price of fuel. We conducted a sensitivity analysis to evaluate how the relative profitability of treatments included in the 2011–12 field trials changed when the price of propane changed. The base propane price for the analysis was US\$0.69 per liter, the 13 Sept. 2011 price. The price of propane had fallen considerably since the fall of 2011. The price was US\$0.45 per liter on 23 May 2013. Considering substantial difference in the propane price over time, we examined the effect of the lower propane price observed in May 2013 on the distribution of net returns. We followed the same procedure as in the base model using the May 2013 propane price.

Results and Discussion

Returns net of treatment, weeding, and harvest labor cost. Total returns net of treatment, weeding, and harvest labor costs for all treatments were summarized in Table 1 (2011–12) and Table 2 (2012–13). The first row of the table reported mean values of net returns calculated using observed data. For both production seasons, mean net returns for all treatments were positive. In the 2011–12 production season, the mean net returns for steam at the MBA site were lower than the mean for CP + 1,3-D and slightly higher than the mean for the untreated control. In the Spence site, however, the mean net returns for steam were the lowest, and they were considerably below the mean net returns for CP + 1,3-D. In the 2012–13 production season, the mean net returns for steam was the highest. Both steam and steam + MSM had substantially higher mean net returns than the untreated control did. The second row of the table reported the standard deviations. At the MBA site in 2011–12, steam had the smallest standard deviation, whereas its standard deviation was similar to those for CP + 1,3-D and the untreated control at the Spence site. In 2012–13, the untreated control had the smallest standard deviation, and the standard deviations of steam and steam + MSM were similar.

The simulated distribution of net returns provided additional information regarding the relative performance of the treatments.

Figures 1–3 plotted the distribution of net returns by treatment for each site and production season. In each figure, the horizontal axis was numerical, representing the value of net returns, and the vertical axis was categorical, representing the treatments. For each box, the lower the variance, the smaller the width of the box; that meant that if the data were more concentrated, the box was narrower. Lines from the left to the right of each box plot presented the value of net returns at the lower adjacent value, the 25th percentile, median, the 75th percentile and the upper adjacent value. Adjacent values at each end were the extreme values within X equal to 1.5 times of the difference between the upper quartile and the lower quartile. The upper adjacent value was the largest value that was less or equal to the sum of the upper quartile and X. The lower adjacent value was the smallest value that was greater than or equal to the difference between the lower quartile and X. In all three box plots, outliers (outside values) that were more than 1.5 times the difference between upper and lower quartiles were excluded (Tukey, 1977).

Next, we compared net returns across pairs of treatments at each site for each production season (Table 3). Relative performance varied considerably between the two 2011–12 sites. The probabilities that steam and CP + 1,3-D would have had higher net returns than the untreated control at the MBA site were 51.3% and 56.9%, respectively. At the Spence site, in contrast, the probability that the steam treatment would have generated higher net returns than the untreated control was only 5.4%, whereas for CP + 1,3-D it was 78.3%. The probability that the net returns for the steam treatment would have been larger than the net returns for the CP + 1,3-D treatment was 41.3% at the MBA site and only 0.6% at the Spence site. In summary, steam and CP + 1,3-D performed similarly at the MBA site, whereas at the Spence site steam was unlikely to have higher net returns than the CP + 1,3-D and would seldom exceed the net returns for the untreated control. This suggested that under some conditions steam may perform similarly to CP + 1,3-D and better than the untreated control, while under other conditions this was highly unlikely to be the case.

Table 1. Returns net of treatment costs, weeding costs, and harvest labor costs by treatment and site (US\$/ha): in 2011–12 growing season in annual plasticulture strawberry production in Central Coast region of California.

	MBA			Spence		
	Steam	CP + 1,3-D ²	Untreated	Steam	CP + 1,3-D	Untreated
Mean	27,092.71	28,516.55	26,832.93	13,234.31	19,063.43	17,229.03
SD	2,077.24	6,041.13	7,741.90	1,671.42	1,426.90	1,810.95

MBA = Monterey Bay Academy.

²CP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39.

Table 2. Returns net of treatment costs, weeding costs, and harvest labor costs by treatment (US\$/ha): trials at a commercial research field, in 2012–13 growing season, in annual plasticulture strawberry production in Central Coast region of California.

	Steam	Steam + MSM	Untreated
Mean	56,637.40	51,764.08	26,069.91
SD	15,368.21	13,443.96	1,729.03

MSM = mustard seed meal.

Fig. 1. Box plots of returns net of treatment costs, weeding costs, and harvest labor costs by treatment (US\$/ha): MBA, in 2011–12 production season, in annual strawberry plasticulture production system in Central Coast region of California.

Fig. 2. Box plots of returns net of treatment costs, weeding costs, and harvest labor costs by treatment (US\$/ha): Spence, in 2011–12 production season, in annual strawberry plasticulture production system in Central Coast region of California. CP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39.

Fig. 3. Box plots of returns net of treatment costs, weeding costs, and harvest labor costs by treatment (US\$/ha): trials at a commercial research field, in 2012–13 production season in annual strawberry plasticulture production system in Central Coast region of California. CP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39, MSM = mustard seed meal.

Table 3. Base case with normally distributed yield and weeding time: probabilities of pairwise comparisons of returns net of treatment costs, weeding costs, and harvest labor costs by treatment, site, and production season in annual strawberry plasticulture production system in Central Coast region of California.

	2011–12		2012–13
	MBA (%)	Spence (%)	TCR (%)
$P^z (NR_{\text{steam}} \geq NR_{\text{CP} + 1,3\text{-D}}^y)$	41.3	0.6	—
$P (NR_{\text{CP} + 1,3\text{-D}} \geq NR_{\text{control}})$	56.9	78.3	—
$P (NR_{\text{steam}} \geq NR_{\text{control}})$	51.3	5.4	97.6
$P (NR_{\text{steam}} \geq NR_{\text{steam} + \text{MSM}})$	— ^x	—	59.5
$P (NR_{\text{steam} + \text{MSM}} \geq NR_{\text{control}})$	—	—	97.3

MBA = Monterey Bay Academy, MSM = mustard seed meal, NR = net returns, TCR = trials at a commercial research field.

^zProbability that the net returns from the steam treatment are larger or equal to those from the CP + 1,3-D treatment.

^yCP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39.

^xThe corresponding pair of treatments was not conducted.

The differences in relative performance between the two sites suggested that site-specific characteristics must be considered when deciding whether to use steam to treat buffer zones. One complicating factor for this decision-making process was that fields facing high pest and disease pressures may benefit the most over the course of multiple seasons from steam's ability to reduce the growth of pests and disease in the buffer zone and hence reduce their spread into the rest of the field, but this effect would not necessarily have been observed in single-year economic returns.

In the 2012–13 production season, compared with the untreated control the mean increase in net returns per hectare due to applying steam was US\$30,567.49 and due to using steam + MSM was US\$25,694.17. Steam and steam + MSM were estimated to have higher net returns than the untreated control 97.6% and 97.3% of the time, respectively. These results indicated that in the 2012–13 trial, the net returns generated by strawberry production were increased significantly (as shown by the change in net returns) and reliably (as shown by the distributions of net returns) by treating the ground with steam or steam + MSM, rather than leaving it untreated. The estimated probability that the net returns for the steam treatment would have been higher than that for the steam + MSM treatment was 59.5%. Switching from steam to steam + MSM would have led to a US\$4865.95/ha decrease in expected net returns.

Sensitivity analysis: alternative yield distribution specifications. Changing the yield distribution from the normal distribution to the t distribution led to insignificant changes in the value of probabilities of pairwise comparisons of net returns as presented in Table 4.

Imposing a nonstandard beta distribution with an upper bound equal to the highest cumulative yield in plot level observed for each treatment increased the probability that the net returns for the steam treatment would have been higher than that for the steam + MSM treatment at the TCR site and decreased the probability of the rest of the pairwise comparisons as presented in Table 5. Increasing the upper bound, however, reduced the changes in the value of probabilities caused by the alternative nonstandard beta distribution. When the upper bound of the nonstandard beta distribution equaled 115% of the highest cumulative yield in plot level observed, the probabilities of pairwise comparisons of net returns were insignificantly different from the ones reported in the base case, in which yield was assumed to be normally distributed.

Sensitivity analysis: learning and adoption of new technology and propane price decrease. Incorporating learning and the adoption of a two-bed applicator resulted in a smaller loss from switching from CP + 1,3-D to steam at both sites (Table 6). The probabilities that the net returns from steam would have been greater than or equal to the net returns from CP + 1,3-D or the untreated

Table 4. Sensitivity analysis with t distributed yield: probabilities of pairwise comparisons of returns net of treatment costs, weeding costs, and harvest labor costs by treatment, site, and production season in annual strawberry plasticulture production system in Central Coast region of California.

	2011–12						2012–13		
	MBA			Spence			TCR		
	df ^z = 10 (%)	df = 20 (%)	df = 30 (%)	df = 10 (%)	df = 20 (%)	df = 30 (%)	df = 10 (%)	df = 20 (%)	df = 30 (%)
P ^y (NR _{steam} ≥ NR _{CP + 1,3-D} ^x)	41.6	41.5	41.3	1.4	1.0	0.9	—	—	—
P (NR _{CP + 1,3-D} ≥ NR _{control})	56.5	56.7	56.9	76.9	77.6	77.8	—	—	—
P (NR _{steam} ≥ NR _{control})	51.3	51.4	51.4	7.0	6.2	6.0	96.1	96.9	97.1
P ^z (NR _{steam} ≥ NR _{steam + MSM})	— ^w	—	—	—	—	59.0	59.3	59.4	—
P (NR _{steam + MSM} ≥ NR _{control})	—	—	—	—	—	—	95.9	96.6	96.8

MBA = Monterey Bay Academy, MSM = mustard seed meal, NR = net returns, TCR = trials at a commercial research field.

^zthe df of a *t* distribution.

^yProbability that the net return from steam treatment is larger than or equal to that from CP + 1,3-D treatment.

^xCP + 1,3-D = chloropicrin: 1,3-dichloropropene 59.6:39.

^wThe corresponding pair of treatments was not conducted.

Table 5. Sensitivity analysis with nonstandard beta distributed yield: probabilities of pairwise comparisons of returns net of treatment costs, weeding costs, and harvest labor costs by treatment, site, and production season in annual strawberry plasticulture production system in Central Coast region of California.

	2011–12						2012–13		
	MBA			Spence			TCR		
	M ^z (%)	110% M	115% M	M (%)	110% M	115% M	M (%)	110% M	115% M
P ^y (NR _{steam} ≥ NR _{CP + 1,3-D} ^x)	32.6	37.0	38.9	0.8	0.6	0.6	—	—	—
P (NR _{CP + 1,3-D} ≥ NR _{control})	55.2	56.0	56.3	80.4	78.5	78.2	—	—	—
P (NR _{steam} ≥ NR _{control})	43.9	47.3	49.1	5.5	5.5	5.5	94.2	95.5	96.4
P (NR _{steam} ≥ NR _{steam + MSM})	— ^w	—	—	—	—	—	65.0	61.2	60.0
P (NR _{steam + MSM} ≥ NR _{control})	—	—	—	—	—	—	93.8	95.1	96.0

MBA = Monterey Bay Academy, MSM = mustard seed meal, NR = net returns, TCR = trials at a commercial research field.

^zM—the highest cumulative yield in plot level observed for each treatment. We have three cases with an upper bound of the nonstandard beta distribution of yield respectively the same as, 110%, and 115%, respectively, of M.

^yProbability that the net returns from the steam treatment is larger than or equal to those from the CP + 1,3-D treatment.

^xCP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39.

^wThe corresponding pair of treatments was not conducted.

Table 6. Sensitivity analysis: expected difference in returns net of treatment costs, weeding costs, and harvest labor costs by treatment and site (US\$/ha) of steam minus CP + 1,3-D^z.

	MBA	Spence
Base case	–1,425.30	–5,831.59
Learning and adoption of new technology	–954.14	–5,371.37
Propane price decrease	1,221.46	–3,195.78

MBA = Monterey Bay Academy.

^zCP + 1,3-D = chloropicrin + 1,3-dichloropropene 59.6:39.

Table 7. Sensitivity analysis: probability of pairwise comparisons of returns net of treatment costs, weeding costs, and harvest labor costs by treatment and site: in 2011–12 production season in annual strawberry plasticulture production system in Central Coast region of California.

	P ^z (NR _{steam} ≥ NR _{CP + 1,3-D} ^x) (%)	P (NR _{steam} ≥ NR _{control}) (%)
MBA		
Base case	41.3	51.3
Learning and adoption of new technology	44.0	53.5
Propane price decrease	57.6	64.3
Spence		
Base case	0.6	5.4
Learning and adoption of new technology	1.1	7.8
Propane price decrease	8.6	29.2

MBA = Monterey Bay Academy.

^zProbability that the net returns from the steam treatment are larger than or equal to those from the CP + 1,3-D treatment.

^yNR is returns net of treatment costs, weeding costs, and harvest labor costs.

^xCP + 1,3-D = chloropicrin: 1,3-dichloropropene 59.6:39.

control increased (Table 7). As a result of learning by doing and increased economies of scale, steam could become a competitive alternative for CP + 1,3-D under a larger set of production conditions in the near future.

With the lower propane price, the gain in the expected net returns from switching from

CP + 1,3-D to steam became positive and significantly different from zero at the MBA site. At the Spence site, expected net returns from switching from CP + 1,3-D to steam were still negative but were smaller in magnitude. At both sites, the lower propane price and associated increase in net returns

increased the probability that net returns for steam would have been larger than for the other treatments (Table 7). A higher propane price would have had the opposite effect: the expected net returns from steam would have declined, and the negative expected change in net returns from switching to steam would have increased in magnitude. The probability that net returns for steam were larger than for the other treatments would have declined.

Discussion

Regulations increasingly limit the use of fumigants for preplant soil disinfestation. Growers need technically and economically feasible alternatives which comply with agrienvironmental regulations. Due to the rapidly evolving regulatory environment in California, the time required for repeated field trials exceeds the regulatory timeframe; information regarding the variability in the economic performance of steam as a means of soil disinfestation as well as its expected performance using the information from limited field trials thus is valuable for growers. This analysis contributed to addressing this need by evaluating the economic feasibility of steam as a nonchemical method of preplant soil disinfestation in the context of California strawberry production. Field trials are costly, and seldom, if ever, include a sufficient number of replicates for statistical estimates of the distributions of yield and weeding times. We used Monte Carlo techniques and sensitivity analysis to provide as much information as possible regarding the economic

performance of the treatments included in the field trials we evaluated.

Reporting only a partial budget analysis using means from the field trials would have provided growers, policymakers, and other stakeholders with less information regarding researchers' assessment of factors likely to influence the economic viability of steam application over time than the Monte Carlo simulations and sensitivity analyses we conducted. Importantly, while its average net returns were lower than those of CP + 1,3-D, net returns from steam exceeded those from CP + 1,3-D almost half the time at the MBA site in the simulation. In other words, steam has the potential to be an economically viable alternative to preplant soil fumigation for California strawberry production in some cases, given reductions in application time that can reasonably be expected to be achieved. Also importantly, steam with or without MSM was shown to improve net returns consistently relative to leaving soil untreated. Using the variability observed in the field trials, sensitivity analysis of key variables and checks of the robustness of the results to the specified yield distribution enabled us to provide information regarding the anticipated reliability of the treatment.

Literature Cited

- American Society of Farm Managers and Rural Appraisers-California Chapter. 2015. Trends in agricultural land and lease values. Calif. State Board of Food and Agri. 4 Jan. 2017. <https://www.cdffa.ca.gov/state_board/pdfs/Presentations/1ErikRoget.pdf>.
- An, H., R. Goodhue, P. Howard, and R. Howitt. 2009. Effects of the Jan. 2008 California Department of Pesticide Regulation field fumigation rules: Ventura County. Calif. Dept. Food and Agri. 4 Jan. 2016. <<https://www.cdffa.ca.gov/files/pdf/goodhuehowitt042309.pdf>>.
- Atwood, J., S. Shaik, and M. Watts. 2003. Are crop yields normally distributed? A reexamination. *Amer. J. Agr. Econ.* 85(4):888–901.
- Bahk, B. and M. Gort. 1993. Decomposing learning by doing in new plants. *J. Polit. Econ.* 101(4): 561–583.
- Boehlje, M.D. and V.R. Eidman. 1984. *Farm Management*. Wiley, NY.
- Bolda, M.P., L. Tourte, K.M. Klonsky, and R.L. De Moura. 2010. Sample costs to produce strawberries Central Coast Region-Santa Cruz & Monterey Counties-2010. ST-CC-10. Univ. Calif. Coop. Ext.
- California Department of Food and Agriculture. 2013. Calif. Agr. Stat. Overview: 2013–2014. 7 May 2015. <<http://www.cdffa.ca.gov/Statistics/>>.
- California Department Pesticide Regulation. 2015a. Chloropicrin mitigation measures: Control of resident and bystander acute exposure from soil fumigation applications. Sacramento.
- California Department Pesticide Regulation. 2015b. Pesticide use reporting data. 7 May 2015. <<http://calipr.cdpr.ca.gov/main.cfm>>.
- Døving, A. 2004. Prediction of strawberry season and yield. *Acta Hort.* 654:325–332.
- Døving, A. and F. Måge. 2001. Prediction of strawberry fruit yield. *Acta Agr. Scandinavica* 51(1):35–42.
- Fennimore, S.A., F.N. Martin, T.C. Miller, J.C. Broome, N. Dorn, and I. Greene. 2014. Evaluation of a mobile steam applicator for soil disinfestation in California strawberry. *Hort-Science* 49:1542–1549.
- Fennimore, S.A., R. Serohijos, J.B. Samtani, H.A. Ajwa, K.V. Subbarao, F.N. Martin, O. Daugovish, D. Legard, G.T. Browne, J. Muramoto, C. Shennan, and K. Klonsky. 2013. TIF film, substrates, and nonfumigant soil disinfestation maintain fruit yields. *Calif. Agr.* 67:139–146.
- Gibbons, J.M. and S.J. Ramsden. 2005. Robustness of recommended farm plans in England under climate change: A Monte Carlo simulation. *Clim. Change* 68:113–133.
- Harri, A., C. Erdem, K.H. Coble, and T.O. Knight. 2009. Crop yield distributions: A reconciliation of previous research and statistical tests for normality. *Appl. Econ. Perspect. Policy* 31(1):163–182.
- Hartley, K. 1965. The learning curve and its application to the aircraft industry. *J. Ind. Econ.* 13(2):122–128.
- Hennessy, D.A. 2009a. Crop yield skewness and the normal distribution. *J. Agr. Resource Econ.* 34:34–52.
- Hennessy, D.A. 2009b. Crop yield skewness under law of the minimum technology. *Amer. J. Agr. Econ.* L91(1):197–208.
- Just, R.E. and Q. Weninger. 1999. Are crop yields normally distributed? *Amer. J. Agr. Econ.* 81(2): 287–304.
- Lien, G. 2003. Assisting whole-farm decision-making through stochastic budgeting. *Agr. Syst.* 76(2):399–413.
- López, A., C. Pérez, A. Arias, J. Palanco, A. Gómez, M. Torres, and M. Rodríguez. 2014. Strawberry fruit yield forecast based on Montecarlo methodology and artificial vision. *Acta Hort.* (1049):551–552.
- Nakamura, T. and H. Ohashi. 2008. Effects of technology adoption on productivity and industry growth: A study of steel refining furnaces. *J. Ind. Econ.* 56(3):470–499.
- Samtani, J.B., H.A. Ajwa, J.B. Weber, G.T. Browne, S. Klose, J. Hunzie, and S.A. Fennimore. 2011. Evaluation of non-fumigant alternatives to methyl bromide for weed control and crop yield in California strawberries. *Crop Prot.* 30:45–51.
- Samtani, J.B., C. Gilbert, J.B. Weber, K.V. Subbarao, R.E. Goodhue, and S.A. Fennimore. 2012. Effect of steam and solarization treatments on pest control, strawberry yield, and economic returns relative to methyl bromide fumigation. *Hort-Science* 47:64–70.
- Tukey, J.W. 1977. *Exploratory Data Analysis*. Wesley, Boston, MA.
- U.S. Dept. Agr., Agricultural Mktg. Serv. 2015. Weekly advertised fruit and vegetable retail prices. 7 May 2015. <<https://www.marketnews.usda.gov/mnp/fv-home>>.
- Wu, F., Z. Guan, and V. Whitaker. 2015. Optimizing yield distribution under biological and economic constraints: Florida strawberries as a model for perishable commodities. *Agr. Syst.* 141:113–120.