Research Reports

Economic Analysis of Anaerobic Soil Disinfestation for Open-field Fresh-market Tomato Production in Southwest and North Florida

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SUMMARY. With the phase-out of methyl bromide due to its impact on ozone depletion, research has focused on developing alternative chemical and biologically based soil disinfestation methods. Anaerobic soil disinfestation (ASD) was developed to control plant-parasitic nematodes, weeds, and soilborne pathogens. However, whether farmers will adopt ASD methods on a large scale is unknown. This study evaluates the economic viability of using ASD in open-field, fresh-market tomato (*Solanum lycopersicum*) production, drawing on data from field experiments conducted in 2015 in Immokalee, FL, and Citra, FL. The experiment included three treatments: chemical soil fumigation (CSF), ASD1 [the standard ASD treatment with 1482 gal/acre molasses and 9 tons/acre composted poultry litter (CPL)], and ASD0.5 (the reduced rate ASD treatment with 741 gal/acre molasses and 4.5 tons/acre CPL). Results from the economic analysis show that ASD treatments require higher labor costs than CSF regarding land preparation and treatment application. However, yields from ASD treatments are higher than those resulting from CSF, and the improvement in yield was enough to offset the increased labor costs. Relative to CSF, ASD0.5, and ASD1 achieved additional net returns of \$630.38/acre and \$2770.13/acre, respectively, in Immokalee, FL. However, due to unexpected conditions unrelated to soil treatments, the net return of ASD1 was lower than that of CSF in Citra, FL. Breakeven analysis indicates that ASD treatments would remain favorable even with an increase in the molasses price. However, when the tomato price is low, ASD could potentially lose its advantage over CSF.

Soilborne diseases and plant-parasitic nematodes have an adverse effect on vegetable crops, causing substantial yield reduction and economic loss. For years, CSF, based primarily on mixtures of methyl bromide and chloropicrin, was widely used for effective soil disinfestation

in horticultural crop production (Butler et al., 2014). With the phase-out of methyl bromide, as part of the Montreal Protocol to reduce ozone depletion, research has focused on developing alternative chemical and biological soil disinfestation methods (Roskopf et al.,

2005). The chemical fumigants used as a replacement for methyl bromide are less effective, particularly for controlling weeds and pathogens with a wide range of hosts. Moreover, chemical fumigation continues to raise concerns for its potential negative impact on human health and the environment (Duniway, 2002; Tsai, 2010). Research is being conducted to find more sustainable and technically feasible nonchemical alternatives to CSF (Fennimore et al., 2013; Shennan et al., 2014), such as crop rotation, soil flooding (especially for nematodes), soil solarization, biofumigation, soil disinfestation with steam, soilless growing systems, and ASD (Larkin, 2015; Molendijk et al., 2009; Roskopf et al., 2005, 2015).

ASD is a biologically based disinfestation, also known as biological soil disinfestation (BSD) method developed in the Netherlands and Japan as an alternative to chemical soil disinfestation to suppress plant-parasitic nematodes, weeds, and soilborne pathogens (Blok et al., 2000; Shinmura, 2000). The approach used for ASD implementation in Florida uses readily decomposable and labile organic carbon sources, such as sugarcane blackstrap molasses (a byproduct of sugar production) combined with CPL to improve soil organic matter and stimulate rapid microbial growth, respiration, and oxygen (O₂) consumption in the soil. Totally impermeable film (TIF), a gas-impermeable opaque plastic film is then used to seal the soil and limit gas exchange between soil and air. Before crop planting, irrigation water is applied to saturate the soil pore space for temporary development of anaerobic conditions, which enhances the diffusion through the soil solution of microbial metabolic byproducts such as organic acids and volatile organic compounds that are suppressive to soilborne pests and diseases (Butler et al., 2012; Momma, 2015; Roskopf et al., 2015). ASD has been applied for suppressing pests and diseases in andisol, alluvial, and sandy soils, as well as artificial substrates, in several cropping systems under various environmental conditions (Lamers et al., 2010; Momma et al., 2013; Roskopf et al., 2015; Shennan et al., 2014; Strauss and Kluepfel, 2015). In many studies, ASD resulted

in higher or similar crop yields to those achieved using chemical fumigation methods (Butler et al., 2014; Di Gioia et al., 2016; Guo et al., 2017; Korthals et al., 2014; Mazzola et al., 2018; Paudel et al., 2018). Researchers in the Netherlands used ASD successfully in asparagus (*Asparagus officinalis*) and strawberry (*Fragaria ×ananassa*) production by combining different techniques, such as soil solarization, organic amendment applications, and soil saturation (Molendijk et al., 2009). The studies in the Netherlands show that ASD has the potential to be a sustainable management strategy to control various soilborne pathogens [e.g., *Fusarium oxysporum*, *Rhizoctonia solani* AG3, *Sclerotinia sclerotiorum* (Blok et al., 2000; Korthals et al., 2014; Messiha et al., 2007)].

Regardless of the ASD benefits, increased labor and material costs, compared with CSF, primarily associated with the use of the carbon source, remain a major concern for the economical use of ASD in commercial production systems (Molendijk et al., 2009; Roskopf et al., 2015). Most previous studies focused on the biological impacts of ASD, examining the effects on disease and pest suppression (Roscopf et al., 2015), microbial communities (Guo et al., 2018; van Agtmaal et al., 2015), crop yield, plant growth, and nutrient cycling (Butler et al., 2014; Di Gioia et al., 2017), rather than on the economics (costs and returns) of ASD. In Florida, in an attempt to increase ASD adoption as an

alternative to chemical fumigation on a large scale, a consistent effort has been made in recent years to develop a more sustainable and economically feasible ASD method concerning optimization of inputs needed for ASD treatment (Di Gioia et al., 2016, 2017; Guo et al., 2017; Paudel et al., 2018). However, the search for alternative approaches to reduce the costs while maintaining or increasing yields making ASD more affordable to growers, continues to be a major task for ASD research. For a broader adoption of ASD among U.S. growers, ASD must be as profitable as, or more profitable than, other alternatives for soil disinfection. Ultimately, it is the impact on profitability that drives the adoption decision for new production practices (Griliches, 1957; Rogers, 2010).

The purpose of this study was to evaluate the economic feasibility of ASD compared with conventional CSF for open-field fresh-market tomato production. Costs and returns of three soil disinfection treatments applied to open-field fresh-market tomato production were compared using results from trials conducted at two agricultural research stations in north (Citra, FL) and south (Immokalee, FL) Florida. Tomato is Florida's second most valuable crop, accounting for 39% of the total U.S. fresh-market tomato production in 2017 [U.S. Department of Agriculture (USDA), 2018]. Evaluating the economic impact of ASD application in fresh-market tomato production could have a major impact on the development and adoption of ASD for tomato production in Florida and elsewhere. Moreover, it may also provide essential information on cost-effective application of ASD important for crop

production to move toward long-term sustainability.

Materials and methods

EXPERIMENTAL SITE AND SOIL DISINFESTATION TREATMENTS. In Fall 2015, identical experiments were conducted for open-field fresh-market tomato production using ASD and CSF methods at the Southwest Florida Research and Education Center in Immokalee, FL, and the Plant Science Research and Education Unit in Citra, FL. At Citra, the experiment began on 13 Aug. 2015, with the crop planted on 3 Sept. 2015, and tomatoes harvested from 10 Nov. to 8 Dec. 2015. At Immokalee, the experiment began on 22 Sept. 2015, with the crop planted on 13 Oct. 2015, and the tomatoes harvested from 4 to 26 Jan. 2016. In both locations, CSF was applied using 119.2 lb/acre chloropicrin + 78 lb/acre 1,3-dichloropropene (Pic-Clor 60; Soil Chemical Corp., Hollister, CA). Because of the price of molasses and the potential environmental risk associated with the use of CPL rich in phosphate, two ASD treatments (ASD1 and ASD0.5) differing in the application rates of molasses and CPL were examined. ASD1, the standard ASD treatment was applied using 1482 gal/acre molasses (Agricultural Carbon Source; Terra Feed, Plant City, FL) and 9 tons/acre CPL (Boyd Brothers, Live Oak, FL). ASD0.5 was applied using 741 gal/acre molasses and 4.5 tons/acre CPL. A randomized complete block design with four replications was used in both locations. At Immokalee, each of the four replicate blocks consisted of one 248-ft-long, 3-ft-wide raised bed divided into three 80-ft-long sections with 4 ft between sections and a bed spacing of 6 ft. At Citra, each bed was 80 ft

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil(s)	mm	39.3701
70.0532	oz/acre	g·ha ⁻¹	0.0143
2.2417	ton(s)/acre	Mg·ha ⁻¹	0.4461

long and 3 ft wide with 6-ft bed spacing.

LAND PREPARATION AND TREATMENT APPLICATION PROCESS. Before forming the raised beds, the land preparation process began at each location with the application of pre-plant fertilizer containing nitrogen (N), phosphorus (P), and potassium (K) according to standard practices (Ozores-Hampton et al., 2015) for all three treatments. N, P, and K were applied at the rate of 30, 43.7, and 33 lb/acre, respectively (Immokalee) and at 50, 21.4, and 41 lb/acre, respectively (Citra). In both locations, the starter fertilizer mix was broadcast applied to the soil surface on bands of 24 inches wide in the area for bed formation. False beds were then formed for soil amendment application. The ASD beds were amended with CPL and with a 1:1 (v:v) water dilution of sugarcane molasses at the defined rates for both ASD1 and ASD0.5. Afterward, the soil was tilled to a depth of 8 inches with a rotary cultivator. Beds were then formed with a regular bed shaper and mulched with 1.18-mil white/black TIF polyethylene mulch containing an ethylene vinyl alcohol barrier layer (VaporSafe; Raven Industries, Sioux Falls, SD). Simultaneously, two drip irrigation lines [8 inches emitter spacing, 0.26 gal/h emitter rate (Jain Irrigation, Haines City, FL)] were installed under the mulch in each bed, at $\approx$ 1-inch depth and 8 inches apart from the center of the bed. Following Butler et al. (2012), ASD plots were irrigated for $\approx$ 4 h at the rate of 2 inches of water (based on raised-bed area only) to saturate the air-filled pore space in the top 4 inches of the bed and enhance the development of anaerobic conditions by reducing the initial soil O₂ concentration and keeping the soil at field capacity. After bed formation, the CSF (control) plots were fumigated by shank injection with chloropicrin + 1,3-dichloropropene at the defined rate, and were mulched with TIF immediately following fumigation.

In both locations and for all the soil disinfestation treatments tested, before mulching the beds with TIF, all the experimental plots were split into two portions (sprayed and not sprayed), with one-half of each plot area treated with 0.75 oz/acre

halosulfuron-methyl (Sanda; Gowan Co., Yuma, AZ) preemergent herbicide. The herbicide application influenced weed control, but not total marketable yield or fruit quality in either location (Guo et al., 2017). Therefore, for the purpose of the economic analysis, the average yield of plots with and without herbicide application was considered.

Three weeks after treatment application, tomato seedlings of the third-true-leaf stage were transplanted. For the tomato cultivars, Tribute (Sakata, Morgan Hill, CA) was planted in Citra, FL, and Ridge Runner (Syngenta, Greensboro, NC) was planted in Immokalee, FL, reflecting grower choice in each region.

TOMATO PRODUCTION MANAGEMENT AND TOMATO HARVESTS. In-season fertigation (consisting of potassium nitrate and ammonium nitrate) for tomato production was applied through drip tapes in both locations. At Immokalee, biweekly (twice per week) fertigation was used, starting 3 weeks after transplanting, whereas Citra used weekly fertigation, starting 7 d after transplanting. The fertilization program information was detailed in Guo et al. (2017). The posttransplant fertigation resulted in the application of 161 lb/acre N and 263 lb/acre K in Immokalee and 144 lb/acre N and 159 lb/acre K in Citra. The total N, P, K fertilizer application rates including pre- and posttransplant fertilizer were 192, 44, and 296 lb/acre, respectively (Immokalee) and 194, 21, and 200 lb/acre, respectively (Citra). The same fertilization program was applied to all the treatments so that the differences between treatments were due only to the soil treatments. Foliar pests and diseases were managed following the University of Florida/Institute of Food and Agricultural Sciences recommendation based on weekly scouting (Freeman et al., 2014).

Tomato harvest was performed on 4, 12, and 26 Jan. 2016 in Immokalee, FL, and 10, 17, and 24 Nov. and 1 and 8 Dec. 2015 in Citra, FL. The harvested fruit were evaluated according to USDA tomato grade standards (USDA, 1991) as extra-large (larger than 2.8 inches diameter), large (from 2.5 to 2.8 inches diameter), medium (from 2.25 to 2.5 inches diameter), or culls (less than 5.25 inches diameter; small and

defective fruit, not included in marketable yield).

Economic analysis

PARTIAL BUDGET ANALYSIS. Partial budget analysis (Kay and Edwards, 1994; Sydorovych et al., 2008; Wossink and Osmond, 2002) is a useful analytical method that compares details that contribute to added or reduced costs and returns between treatments. In the current study, the added expenses of ASD were considered the adverse effects, whereas the added gross returns of ASD were the positive effects. Whether the increased marketable fruit yield can offset the additional costs associated with ASD was determined by the increased gross return associated with the yield increase in ASD.

The principal formulas used in budget analysis are as follows. First, the total cost is calculated as follows:

$$TC = \text{Land Preparation Cost} \\ + \text{Production Cost} \\ + \text{Harvesting Cost} \\ + \text{Marketing Cost} \quad [1]$$

where TC (\$/acre) is the total cost, and the four types of costs include both material and labor cost (\$/acre) for the entire tomato growing season from land preparation (including soil treatments) to harvest.

Once the harvested tomatoes were categorized by size, the corresponding tomato yields resulting from each of the treatments were collected. Marketable tomato grade classes, as measured by fruit size, result in the receipt of a price differential. The tomato prices [P_i (shipping point price)] of different sizes (extra-large, large, and medium) were obtained from the USDA Agricultural Marketing Service (USDA, 2015) that provides daily tomato prices at multiple locations (e.g., Central District CA, Central and South FL, West District FL) in the United States. Using the average prices from multiple locations in Florida, the assumptions were that the harvest dates were the sale dates for tomatoes and that the total marketable yield was sold. Whenever recorded price data were unavailable on a specific harvest date, the average of the two prices that were most close to the harvest date were used (most of the time, the prices within 2 to 3 d of the harvest date). To reduce the bias

Table 1. The cost differences among chemical soil fumigation (CSF) and anaerobic soil disinfestation (ASD) treatments in land preparation for field fresh-market tomato production.

		CSF ^z	ASD0.5 ^y	ASD1 ^x	CSF	ASD0.5	ASD1
		Immokalee, FL			Citra, FL		
\$ /acre ^w	Material cost	1,462.4	1,114.1	1,865.76	1,468.4	1,120.1	1,871.76
	Film	362.45	362.45	362.45	368.45	368.45	368.45
	Fumigant	1,099.95	n/a	n/a	1,099.95	n/a	n/a
	CPL	n/a	284.90	569.80	n/a	284.90	569.80
	Molasses	n/a	466.75	933.51	n/a	466.75	933.51
	Labor	336.27	783.51	1,019.00	336.27	783.51	1,019.00
	Total cost	1,798.69	1,897.62	2,884.77	1,804.67	1,903.60	2,890.75
\$ /plant ^v	Material cost	0.30	0.23	0.39	0.30	0.23	0.39
	Labor	0.07	0.16	0.21	0.07	0.16	0.21
	Total cost	0.37	0.39	0.60	0.37	0.39	0.60
	Added cost of using ASD relative to CSF (\$ /plant)	n/a	0.02	0.22	n/a	0.02	0.22

^z119.2 lb/acre chloropicrin + 78 lb/acre 1,3-dichloropropene; 1 lb/acre = 1.1209 kg·ha⁻¹.

^y741 gal/acre (6931.3 L·ha⁻¹) of molasses and 4.5 tons/acre (10.09 Mg·ha⁻¹) of composted poultry litter (CPL).

^x1482 gal/acre (13,862.6 L·ha⁻¹) of molasses and 9 tons/acre (20.2 Mg·ha⁻¹) of CPL.

^w\$1.00/acre = \$2.4711/ha.

^vPlant density for all the treatments in both locations was 4842 plants/acre (11,964.8 plants/ha).

Table 2. Estimated production costs for field fresh-market tomato production excluding land preparation costs associated with different soil treatments.

Operation (\$/acre) ^z	Immokalee, FL	Citra, FL
Fertilizer and irrigation costs		
Fertilizer in land preparation	454.90	454.90
Fertilizer in production	331.25	331.25
Irrigation materials	426.22	552.41
Electricity for water pumping	12.03	11.17
Total fertilizer and irrigation costs	1,224.39	1,349.72
Operating costs		
Transplant	726.30	726.30
Herbicide	42.50	42.50
Fungicide	275.99	275.99
Pesticide	548.60	548.60
Machinery variable cost and general farm labor ^y	175.00	175.00
Stakes	90.00	90.00
Strings	28.75	28.75
Total operating costs	1,887.14	1,887.14
Fixed costs		
Land rent	500.00	500.00
Service, management and overhead	3,672.20	3,672.20
Total fixed costs	4,172.20	4,172.20
Total preharvest costs	7,283.73	7,409.06

^z\$1.00/acre = \$2.4711/ha.

^yMachinery variable cost included equipment and fuel costs. General farm labor included pesticide and weed management, trellising, scouting, and irrigation labor cost.

introduced by yearly market price fluctuations, for tomato of each size, the average price of the previous 5 years' (2011–15) harvest dates was used. For example, the price used for Immokalee, FL (the harvest was in 2016), is

$$\bar{P}_{i,t} = \frac{P_{i,t2011} + P_{i,t2012} + P_{i,t2013} + P_{i,t2014} + P_{i,t2015}}{5} \quad [2]$$

where $P_{i,t2011}$ to $P_{i,t2015}$ [i = extra-large, large, and medium (\$/25-lb

carton)] were the average tomato shipping prices around harvesting date ($t = 4, 12$, and 26 Jan.) of 2011 to 2015 in Immokalee, FL, respectively. The total revenue is then

$$TR = \sum_t \sum_i Y_{i,t} \bar{P}_{i,t} \quad [3]$$

where TR (\$/acre) is the total revenue, also known as gross return. $\bar{P}_i$ (\$/carton) is the average selling price of tomatoes of size i over the 5 years;

Y_i (cartons/acre) is the quantity harvested/sold of tomatoes of size i .

The net return or profit is calculated as total revenue minus total cost:

$$Profit = TR - TC \quad [4]$$

SENSITIVITY ANALYSIS. Sensitivity analysis is helpful in determining how net return changes under various scenarios in correspondence to a factor and shows the relative importance of the investigated factors (Dalir et al., 2017). It is increasingly used in the agricultural and environmental science fields for decision making at a local scale.

Two types of sensitivity analysis were conducted to examine the changing trend of net returns as influenced by factors. The first type examines the impact of molasses price and tomato selling price on the net return of the three soil disinfestation treatments; the second type examines the impact of tomato yield and tomato selling price on net returns. Molasses accounts for a significant amount of the cost associated with ASD. Meanwhile, it also leads to a higher probability of revenue increases due to increased yield. Therefore, the molasses price is a key factor that determines whether the ASD method is economically comparable to CSF. Various external production factors, such as weather conditions, influence tomato yield; therefore, yield is an important factor that determines the

relative profitability of these treatments. Tomato selling price, which fluctuates significantly by month and year, may also significantly affect gross revenue. To simplify the sensitivity analysis, we used the weighted average tomato price P (Eq. [5]) and the total marketable yield rather than yield based on tomato size for ease of calculation.

The weighted average tomato price for each treatment was calculated as follows:

$$P = \frac{TR}{\sum_i \sum_t Y_{i,t}} \quad [5]$$

where P (\$/carton) is the weighted average tomato price for the total

marketable yield, and $TotalYield$ (cartons/acre) is the total marketable tomato yield of a treatment including all tomato sizes. The calculated weighted average prices were \$10.95 to \$13.95 per carton in Immokalee, FL, and \$11.66 to \$15.02 per carton in Citra, FL, depending on the treatment (the variation in the average price is due to the impact of treatments on fruit size and yield distribution).

BREAKEVEN ANALYSIS. Breakeven analysis can be used to calculate the threshold of a factor (e.g., tomato price, molasses price) when two treatments generate the same net return (Barnard and Nix, 1979; Dillon, 1993; Forster and Erven, 1981). This study implemented two types of breakeven analysis to find the breakeven points for molasses price and tomato yield, at which ASD treatments and CSF would result in the same net return.

Results and discussion

TOTAL COSTS, YIELDS, AND GROSS RETURNS OF TREATMENTS. Table 1 presents the costs of key materials and labor used in land preparation common to all three soil disinfestation treatments. Cost is presented in two ways: cost per acre and cost per plant. The added land preparation costs per plant using ASD relative to CSF is the difference between the cost per plant of ASD and that of CSF.

In both Immokalee, FL, and Citra, FL, the cost of molasses used in ASD treatments contributed significantly to material costs (the commercial molasses price of \$0.63/gal in 2017 was used in this study). The molasses cost accounted for about 25% (in ASD0.5) and 32% (in ASD1) of the total material cost in both locations. The greater the amount of molasses applied in

Table 3. Average marketable tomato fruit yields, harvest costs, and gross returns for field fresh-market tomato production with chemical soil fumigation (CSF) and anaerobic soil disinfestation (ASD).

Item	CSF ^z	ASD0.5 ^y	ASD1 ^x
	Immokalee, FL		
Tomato selling price (\$/25-lb carton) ^w	12.83	12.84	12.88
Total marketable fruit yield (cartons/acre)	1,563.13	1,641.65	1,973.55
Container box material cost ^v	1,172.35	1,231.24	1,480.16
Pick, pack, and haul	4,239.04	4,451.96	5,352.03
Selling and marketing ^u	\$234.47	\$246.25	\$296.03
Organization fee ^t	\$140.68	\$147.75	\$177.62
Total estimated harvest costs (\$/acre) ^s	5,786.54	6,077.19	7,305.84
Harvest costs relative to CSF (\$/acre)	n/a	290.65	1,519.30
Gross returns (\$/acre) ^r	20,051.66 ^a	21,071.62	25,427.16
Gross returns relative to CSF (\$/acre)	n/a	1,019.96	5,375.51
Item	Citra, FL		
	CSF ^z	ASD0.5 ^y	ASD1 ^x
Tomato selling price (\$/carton)	13.14	13.34	13.02
Average marketable fruit yield (cartons/acre)	1,934.29	2,191.24	1,745.14
Container box material cost	1,450.72	1,643.43	1,308.86
Pick, pack, and haul	5,245.57	5,942.40	4,732.63
Selling and marketing	\$290.14	\$328.69	\$261.77
Organization fee	\$174.09	\$197.21	\$157.06
Total estimated harvest costs (\$/acre)	7,160.52	8,111.73	6,460.32
Harvest costs relative to CSF (\$/acre)	n/a	869.84	-640.30
Gross returns (\$/acre)	25,412.35	29,240.25	22,719.16
Gross returns relative to CSF (\$/acre)	n/a	3,827.89	-2,693.19

^z119.2 lb/acre chloropicrin + 78 lb/acre 1,3-dichloropropene; 1 lb/acre = 1.1209 kg·ha⁻¹.

^y741 gal/acre (6931.3 L·ha⁻¹) of molasses and 4.5 tons/acre (10.09 Mg·ha⁻¹) of composted poultry litter (CPL).

^x1482 gal/acre (13,862.6 L·ha⁻¹) of molasses and 9 tons/acre (20.2 Mg·ha⁻¹) of CPL.

^w\$1.00/25-lb (11.3 kg) carton = \$0.0882/kg.

^vThe cost per container box is \$0.75 (VanSickle and Weldon, 2009).

^uSelling and marketing cost is estimated at \$0.15/carton.

^tOrganization fee is a fee charged by The Florida Tomato Committee and Florida Tomato Exchange on all tomato growers in Florida, which is estimated at \$0.09/carton.

^s\$1.00/acre = \$2.4711/ha.

^rGross return = fruit yield × selling price.

^aThe number seems different from the fruit yield × selling price if fruit yield and price provided in the table are used. The reason is that the gross returns that we provided in the table uses the numbers without rounding.

Table 4. Added and reduced costs, reduced and added returns, and total negative and positive effects incurred by field fresh-market tomato production in anaerobic soil disinfestation (ASD) compared with chemical soil fumigation (CSF).

Treatment	Added costs	Reduced returns	Total negative effects	Reduced costs	Added returns	Total positive effects	Total effects of ASD relative to CSF
(\$/acre) ^z							
Immokalee, FL							
ASD0.5 ^y	389.58	0.00	389.58	0.00	1,019.96	1,019.96	630.38
ASD1 ^x	2,605.38	0.00	2,605.38	0.00	5,375.51	5,375.51	2,770.13
Citra, FL							
ASD0.5	1,050.14	0.00	1,050.14	0.00	3,827.89	3,827.89	2,777.75
ASD1	385.88	0.00	385.88	0.00	-2,693.19	-2,693.19	-3,079.08

^z\$1.00/acre = \$2.4711/ha.

^y741 gal/acre (6931.3 L·ha⁻¹) of molasses and 4.5 tons/acre (10.09 Mg·ha⁻¹) of CPL.

^x1482 gal/acre (13,862.6 L·ha⁻¹) of molasses and 9 tons/acre (20.2 Mg·ha⁻¹) of composted poultry litter (CPL).

Table 5. Comparisons of estimated gross returns, costs of land preparation and harvest, other preharvest costs, and total net returns between field fresh-market tomato production with chemical soil fumigation (CSF) and anaerobic soil disinfestation (ASD).

Treatment	Gross returns	Land preparation costs	Harvest costs	Other preharvest costs	Total net returns	Additional net returns relative to CSF
(\$/acre) ^z						
Immokalee, FL						
CSF ^y	20,051.66	1,798.69	5,786.54	7,283.73	5,182.69	0.00
ASD0.5 ^x	21,071.62	1,897.62	6,077.19	7,283.73	5,813.08	630.38
ASD1 ^w	25,427.16	2,884.77	7,305.84	7,283.73	7,952.82	2,770.13
Citra, FL						
CSF	25,412.35	1,804.67	7,160.52	7,409.06	9,038.11	0.00
ASD0.5	29,240.25	1,903.60	8,111.73	7,409.06	11,815.86	2,777.75
ASD1	22,719.16	2,890.75	6,460.32	7,409.06	5,959.03	-3,079.08

^z\$1.00/acre = \$2.4711/ha.

^y119.2 lb/acre chloropicrin + 78 lb/acre 1,3-dichloropropene; 1 lb/acre = 1.1209 kg·ha⁻¹.

^x741 gal/acre (6931.3 L·ha⁻¹) of molasses and 4.5 tons/acre (10.09 Mg·ha⁻¹) of composted poultry litter (CPL).

^w1482 gal/acre (13,862.6 L·ha⁻¹) of molasses and 9 tons/acre (20.2 Mg·ha⁻¹) of CPL.

Table 6. Estimated net returns of field fresh-market tomato production with anaerobic soil disinfestation (ASD), and net return comparisons between chemical soil fumigation (CSF) and ASD tomato production with varying tomato and molasses prices in Immokalee, FL.

Molasses price (\$/gal) ^z	Tomato price (\$/25-lb carton) ^y				
	8.91	10.69	12.83	15.39	18.47
Net return: ASD0.5 (\$/acre) ^x					
0.44	-491.75	2,433.09	5,942.89	10,154.66	15,208.77
0.53	-556.57	2,368.26	5,878.07	10,089.83	15,143.95
0.63	-634.37	2,290.47	5,800.27	10,012.04	15,066.15
0.76	-727.72	2,197.12	5,706.92	9,918.69	14,972.80
0.91	-839.74	2,085.10	5,594.90	9,806.67	14,860.78
Differences between the net return of ASD0.5 and CSF (\$/acre)					
0.44	452.46	592.34	760.20	961.63	1,203.35
0.53	387.63	527.51	695.37	896.81	1,138.52
0.63	309.84	449.72	617.58	819.01	1,060.73
0.76	216.49	356.37	524.23	725.66	967.38
0.91	104.47	244.35	412.21	613.64	855.36
B/E ^w	\$1.05	\$1.24	\$1.46	\$1.74	\$2.06
Net return: ASD1 (\$/acre)					
0.44	391.70	3,907.86	8,127.26	13,190.53	19,266.46
0.53	262.05	3,778.21	7,997.60	13,060.88	19,136.80
0.63	106.46	3,622.62	7,842.02	12,905.29	18,981.22
0.76	(80.24)	3,435.92	7,655.32	12,718.59	18,794.52
0.91	(304.28)	3,211.88	7,431.28	12,494.55	18,570.48
Differences between the net return of ASD1 and CSF (\$/acre)					
0.44	1,335.90	2,067.11	2,944.56	3,997.51	5,261.03
0.53	1,206.25	1,937.46	2,814.91	3,867.85	5,131.38
0.63	1,050.67	1,781.88	2,659.33	3,712.27	4,975.80
0.76	863.96	1,595.17	2,472.62	3,525.57	4,789.09
0.91	639.92	1,371.13	2,248.58	3,301.52	4,565.05
B/E	\$1.34	\$1.83	\$2.42	\$3.14	\$3.99

^zMolasses prices derived by increasing or decreasing in average molasses price (\$0.63/gal) by 20% gradually; \$1.00/gal = \$0.2642/L.

^yTomato market prices derived by increasing or decreasing the average CSF tomato price (\$12.83/carton) by 20% gradually; \$1.00/25-lb (11.3 kg) carton = \$0.0882/kg.

^x\$1.00/acre = \$2.4711/ha.

^wB/E= breakeven molasses price.

ASD, the higher the percentage of material cost relative to the total cost of land preparation and treatment application (ASD0.5 = 59% in Immokalee, FL, and in Citra, FL;

ASD1 = 65% in Immokalee, FL, and in Citra, FL). Labor costs also increased significantly with ASD treatments compared with CSF due to additional labor needed for the

application of CPL and molasses. When calculating the labor cost, the wage rate at both Citra and Immokalee, FL, was estimated at \$10.19/h across the board. This is a reasonable wage estimate. Djidonou et al. (2013) used \$8.45/h in their economic analysis of tomato production in north Florida. The minimum wage rate was \$8.05/h in Florida in 2015 and 2016. And the Adverse Effect Wage Rate (AEWR) for H-2A labor of Florida was \$10.19/h (Federal Register, 2014). Although a significant amount of H-2A labors were used at the two locations that we studied (Huennekens, 2018), they were primarily used for piece-rate work with specialty crops when the farm labor was in high demand. Therefore, \$8.05/h and \$10.19/h could be considered as the lower bound and upper bound, respectively, of the regular farm labor wage rate. In this article, we used the AEWR to be conservative and provide a more rigorous “hurdle rate” to determine economic feasibility. The labor cost was highly correlated with the amount of materials and complexity of the application procedure. For example, because of the additional work-hours spent on applying the ASD procedure, the labor cost for ASD1 was approximately three times the cost for CSF in both Immokalee, FL, and Citra, FL. If ASD were to become a standard practice, labor costs could potentially decrease due to mechanization of the application method.

In general, the total land preparation costs of the same treatment at the two locations were very similar

Table 7. Estimated net returns of field fresh-market tomato production with anaerobic soil disinfestation (ASD), and net return comparisons between chemical soil fumigation (CSF) and ASD tomato production with varying tomato and molasses prices in Citra, FL.

Molasses price (\$/gal) ^z	Tomato price (\$/25-lb carton) ^y				
	9.12	10.95	13.14	15.77	18.92
Net return: ASD0.5 (\$/acre)^x					
0.44	2,710.01	6,708.36	11,506.39	17,264.02	24,173.18
0.53	2,645.18	6,643.54	11,441.56	17,199.20	24,108.36
0.63	2,567.39	6,565.74	11,363.77	17,121.40	24,030.56
0.76	2,474.04	6,472.39	11,270.42	17,028.05	23,937.21
0.91	2,362.02	6,360.37	11,158.40	16,916.03	23,825.19
Differences between the net return of ASD0.5 and CSF (\$/acre)					
0.44	1,436.79	1,905.65	2,468.29	3,143.45	3,953.64
0.53	1,371.96	1,840.82	2,403.46	3,078.62	3,888.82
0.63	1,294.17	1,763.03	2,325.67	3,000.83	3,811.02
0.76	1,200.82	1,669.68	2,232.32	2,907.48	3,717.67
0.91	1,088.80	1,557.66	2,120.29	2,795.46	3,605.65
B/E ^w	2.38	3.01	3.77	4.68	5.77
Net return: ASD1 (\$/acre)					
0.44	-553.10	2,631.26	6,452.49	11,037.96	16,540.54
0.53	-682.75	2,501.60	6,322.83	10,908.31	16,410.88
0.63	-838.34	2,346.02	6,167.25	10,752.73	16,255.30
0.76	-1,025.04	2,159.32	5,980.55	10,566.03	16,068.60
0.91	-1,249.08	1,935.28	5,756.51	10,341.98	15,844.55
Differences between the net return of ASD1 and CSF (\$/acre)					
0.44	-1,826.32	-2,171.45	-2,585.62	-3,082.61	-3,679.00
0.53	-1,955.97	-2,301.11	-2,715.27	-3,212.26	-3,808.66
0.63	-2,111.56	-2,456.69	-2,870.86	-3,367.85	-3,964.24
0.76	-2,298.26	-2,643.39	-3,057.56	-3,554.55	-4,150.94
0.91	-2,522.30	-2,867.44	-3,281.60	-3,778.59	-4,374.99
B/E	n/a ^v	n/a	n/a	n/a	n/a

^zMolasses prices derived by increasing or decreasing in average molasses price (\$0.63/gal) by 20% gradually; \$1.00/gal = \$0.2642/L.

^yTomato market prices derived by increasing or decreasing the average CSF tomato price (\$12.83/carton) by 20% gradually; \$1.00/25-lb (11.3 kg) carton = \$0.0882/kg.

^x\$1.00/acre = \$2.4711/ha.

^wB/E = breakeven molasses price.

^vBreakeven molasses prices in comparing net return between ASD1 and CSF in Citra, FL, were negative, which implies that ASD1 is not economically more profitable at all with the yields from the Citra, FL, trial.

despite fluctuations in the costs of some materials (e.g., TIF). In both locations, ASD1 had the highest total cost among the three treatments and CSF had the lowest total cost. The costs associated with land preparation and treatment application in CSF, ASD0.5, and ASD1 were estimated at \$0.37, \$0.39, and \$0.60 per plant, respectively, in both locations. The cost per plant for ASD0.5 was only slightly higher than that for CSF, but the cost per plant for ASD1 increased substantially. The small difference in film costs between locations was due to the difference in the field experiment layout as previously mentioned.

Table 2 presents the production costs (the same for all three treatments) in both locations. Fixed costs, harvest costs, and marketing costs were estimated based on VanSickle and Weldon (2009) and Djidonou

et al. (2013). The production cost included fertilizer and irrigation costs, operating costs, and fixed costs. For the irrigation materials, there were two parallel drip tapes, two fittings, and one header tube used in each bed. All costs for fertilizer and irrigation, except electricity for water pumping, and all operating costs, including costs for fungicide and insecticides, machinery variable costs, and general farm labor, were based on experimental data.

Information contained in Table 3 summarizes and compares the total harvesting costs, weighted average tomato selling prices, and gross returns. The harvest costs estimated in this study reflected the marketable yields of tomatoes; higher yield led to additional carton costs for packaging and more labor costs for picking, packing, and hauling. The harvest

and post-harvest costs associated with packaging, labor, and marketing were \$5786.54 in Immokalee, FL, and \$7160.52 in Citra, FL, for CSF; \$6077.19 and \$8111.73 for ASD0.5; and \$7305.84 and \$6460.32 for ASD1, respectively. The assumption was that the selling, marketing, and organization fees were the same for all the treatments at both locations.

All raw data related to tomato shipping point prices were from the USDA, Agricultural Marketing Service (USDA, 2015). The tomato price not only depended on fruit size, but also on supply and demand, consumers' preferences, exports, and imports as external factors, and fruit quality as an internal factor. Sometimes larger tomatoes had a lower shipping point price because customers did not always prefer larger fruit at that time. Because different tomato sizes receive different prices, to simplify the analysis, the weighted average tomato selling (shipping point) prices (see Eq. [5]) were calculated. According to the USDA (2015), the tomato annual average farm prices in Florida were \$11.25 per carton in 2013, \$12/carton in 2014, and \$9.75/carton in 2015. Therefore, the average tomato farm price was \$11/carton in Florida in the preceding 3 years. The tomato prices calculated in our experiments were all above \$12.5/carton (Table 3), which were close to or slightly higher than the annual average farm price across Florida. The corresponding average tomato retail price in Florida was \$42.33/carton during the same period. The average marketable yields were 1563.13, 1641.65, and 1973.55 cartons/acre for CSF, ASD0.5, and ASD1, respectively, in Immokalee, FL, and were 1934.29, 2191.24, and 1745.14 cartons/acre, respectively, in Citra, FL (Table 3). Both ASD treatments had higher tomato yields than CSF in Immokalee, FL, but ASD1 had a lower yield than CSF in Citra, FL. This was likely due to a high soil fertility in ASD1 plots, and the cultivar used in Citra, FL, may have responded to the high fertility level by decreasing or delaying flowering and fruit set, as suggested by Guo et al. (2017). Higher yield leads to higher total harvest cost, which is closely related to yield, whereas at the same time, higher yield generates a higher gross return as there is no significant

Table 8. Estimated net returns of field fresh-market tomato production with anaerobic soil disinfestation (ASD), and net return comparisons between chemical soil fumigation (CSF) and ASD tomato production with varying tomato price and yield in Immokalee, FL.

Yield (25-lb cartons/acre) ^z	Tomato price (\$/carton) ^y				
	8.91	10.69	12.83	15.39	18.47
Net return: ASD0.5 (\$/acre)^x					
1,140.03	-3,846.97	-1,815.84	621.51	3,546.34	7,056.13
1,368.04	-2,705.07	-267.71	2,657.12	6,166.91	10,378.66
1,641.65	-1,334.78	1,590.05	5,099.84	9,311.59	14,365.70
1,969.98	309.57	3,819.36	8,031.11	13,085.21	19,150.14
2,363.98	2,282.78	6,494.53	11,548.64	17,613.56	24,891.47
Differences between the net return of ASD0.5 and CSF (\$/acre)					
1,140.03	-2,902.77	-3,656.59	-4,561.18	-5,646.68	-6,949.29
1,368.04	-1,760.86	-2,108.46	-2,525.58	-3,026.11	-3,626.76
1,641.65	-390.57	-250.70	-82.85	118.57	360.27
1,969.98	1,253.77	1,978.61	2,848.42	3,892.19	5,144.71
2,363.98	3,226.99	4,653.79	6,365.94	8,420.53	10,886.04
B/E ^w	1,719.63	1,678.57	1,650.92	1,631.33	1,616.92
Net return: ASD1 (\$/acre)					
1,140.03	-4,834.12	-2,802.99	-365.64	2,559.19	6,068.98
1,368.04	-3,692.22	-1,254.86	1,669.97	5,179.76	9,391.51
1,641.65	-2,321.93	602.90	4,112.69	8,324.44	13,378.55
1,969.98	-677.58	2,832.21	7,043.96	12,098.07	18,162.99
2,363.98	1,295.63	5,507.39	10,561.49	16,626.41	23,904.32
Differences between the net return of ASD1 and CSF (\$/acre)					
1,140.03	-3,889.92	-4,643.74	-5,548.33	-6,633.83	-7,936.44
1,368.04	-2,748.01	-3,095.61	-3,512.72	-4,013.26	-4,613.91
1,641.65	-1,377.72	-1,237.85	-1,070.00	-868.58	-626.88
1,969.98	266.62	991.46	1,861.27	2,905.04	4,157.57
2,363.98	2,239.84	3,666.64	5,378.79	7,433.39	9,898.89
B/E	1,916.74	1,823.95	1,761.49	1,717.22	1,684.66

^zTomato yields derived by increasing or decreasing the ASD0.5 tomato yield (1641.65 cartons/acre) by 20% gradually; 1 25-lb (11.3 kg) carton/acre = 28.0213 kg·ha⁻¹.

^yTomato market prices derived by increasing or decreasing the average CSF tomato price (\$12.83/carton) by 20% gradually; \$1.00/carton = \$0.0882/kg.

^x\$1.00/acre = \$2.4711/ha.

^wB/E = breakeven tomato yield.

difference in tomato selling prices between treatments based on the calculation used.

Similar to previous studies, there was a significant crop yield increase resulting from ASD treatments compared with CSF. For example, ASD treatments in the Netherlands resulted in a 17% to 53% yield increase compared with CSF treatments (Shennan et al., 2014). ASD research in the United States started in California and Florida, and ASD has progressed rapidly as an important potential tool for soil disinfestation for numerous commodities. A 2008–09 field study of bell pepper (*Capsicum annuum*) and eggplant (*Solanum melongena*) in Florida showed that using ASD with molasses as the carbon source resulted in equivalent or higher marketable yields compared with using CSF with methyl bromide. Specifically,

the total yield of eggplant using molasses and CPL was 27.8 tons/acre compared with 18.7 tons/acre using methyl bromide (Butler et al., 2014). More recent work in a Florida tomato production system resulted in a 19.7% to 26.7% yield increase, depending on the quantity of carbon input, using ASD compared with CSF in the spring season (Di Gioia et al., 2016), and no difference or 26.3% yield increase in the fall season (Guo et al., 2017). However, the yield increase in ASD treatments does not always occur. For example, McCarty et al. (2014) did not observe any yield difference for either tomato or bell pepper between the ASD treatments and the untreated control under cool conditions in Tennessee. Therefore, to maximize the economic profitability of ASD treatments, more research is needed to improve ASD treatments,

particularly for regions in which cooler soil temperatures would be associated with the application window.

PARTIAL BUDGET ANALYSIS. Partial budget analysis describes the cost, gross return, and net return related to alternative inputs and outputs. In this study, the added costs of ASD treatments were associated with extra labor and the use of the carbon source (molasses) and organic amendment (CPL). The additional gross return was associated with increased marketable yield and price. The net return for each ASD treatment relative to CSF was presented two ways: 1) the difference between the total positive effects and the total negative effects of ASD (Table 4), and 2) the difference between the gross return and the partial costs (Table 5).

The information provided in Table 4 represents the results of the partial budget analysis. The total negative and positive effects incurred with CSF and ASD treatments were defined as the added cost plus reduced gross return and the reduced cost plus added gross return, respectively. The total effects were the differences between the total positive effects and total negative effects. The total effects of both ASD treatments relative to CSF in Immokalee, FL, were positive, meaning that the values of the total negative effects were lower than the total positive effects. ASD0.5 had positive total effect whereas ASD1 had a negative total effect compared with CSF in Citra, FL. Neither ASD treatment had simultaneous reduced costs and added returns. In these experiments, we have not adjusted the fertilizer rate for ASD treatments. However, ASD treatments with CPL and molasses could help improve soil nutrient availability (Guo et al., 2017) and thus lead to a potential reduction in fertilizer input. This additional benefit of ASD application could be considered in future economic analysis when more research information is available regarding the impact of ASD on crop nutrient management. The positive total effects of ASD relative to CSF implied that ASD treatments could be more profitable than CSF in most cases. In Immokalee, FL, ASD1 was preferred over ASD0.5 due to its much higher added returns, but the relationship reversed in Citra, FL.

Table 9. Estimated net returns of field fresh-market tomato production with anaerobic soil disinfestation (ASD), and net return comparisons between chemical soil fumigation (CSF) and ASD tomato production with varying tomato price and yield in Citra, FL.

Yield (25-lb cartons/acre) ^z	Tomato price (\$/carton) ^y				
	9.12	10.95	13.14	15.77	18.92
Net return: ASD0.5 (\$/acre)^x					
1,211.90	-3,357.47	-1,146.12	1,507.50	4,691.85	8,513.06
1,454.28	-2,091.40	562.22	3,746.56	7,567.78	12,153.24
1,745.14	-572.12	2,612.23	6,433.44	11,018.90	16,521.45
2,094.17	1,251.02	5,072.23	9,657.69	15,160.24	21,763.30
2,513.00	3,438.79	8,024.25	13,526.79	20,129.85	28,053.52
Differences between the net return of ASD0.5 and CSF (\$/acre)					
1,211.90	-4,630.69	-5,948.83	-7,530.60	-9,428.73	-11,706.48
1,454.28	-3,364.62	-4,240.49	-5,291.54	-6,552.80	-8,066.30
1,745.14	-1,845.34	-2,190.49	-2,604.66	-3,101.68	-3,698.09
2,094.17	-22.20	269.52	619.59	1,039.67	1,543.76
2,513.00	2,165.57	3,221.53	4,488.69	6,009.28	7,833.98
B/E ^v	2,098.41	2,055.92	2,027.09	2,006.54	1,991.37
Net return: ASD1 (\$/acre)					
1,211.90	-4,344.62	-2,133.27	520.35	3,704.70	7,525.91
1,454.28	-3,078.55	-424.93	2,759.42	6,580.63	11,166.09
1,745.14	-1,559.27	1,625.08	5,446.29	10,031.75	15,534.30
2,094.17	263.87	4,085.09	8,670.54	14,173.09	20,776.15
2,513.00	2,451.64	7,037.10	12,539.64	19,142.70	27,066.37
Differences between the net return of ASD1 and CSF (\$/acre)					
1,211.90	-5,617.84	-6,935.98	-8,517.75	-10,415.88	-12,693.63
1,454.28	-4,351.77	-5,227.64	-6,278.69	-7,539.95	-9,053.45
1,745.14	-2,832.49	-3,177.64	-3,591.81	-4,088.83	-4,685.24
2,094.17	-1,009.35	-717.63	-367.56	52.52	556.61
2,513.00	1,178.42	2,234.38	3,501.54	5,022.13	6,846.83
B/E ^w	2,287.40	2,195.98	2,133.95	2,089.74	2,057.10

^zTomato yields derived by increasing or decreasing the ASD0.5 tomato yield (1641.65 cartons/acre) by 20% gradually; 1 25-lb (11.3 kg) carton/acre = 28.0213 kg·ha⁻¹.

^yTomato market prices derived by increasing or decreasing the average CSF tomato price (\$12.83/carton) by 20% gradually; \$1.00/ carton = \$0.0882/kg.

^x\$1.00/acre = \$2.4711/ha.

^wB/E = breakeven tomato yield.

Data provided in Table 5 presents a more detailed summary of costs incurred in the three soil treatments in both locations. The total costs included land preparation (including treatment application), harvest, and other preharvest costs. The main additional costs of ASD were reflected in the land preparation and treatment application cost and harvest cost. In Immokalee, FL, ASD1 had the highest land preparation cost and harvest cost. There was no difference in other preharvest costs among treatments in the same location. The net returns (the same as those in Table 4) indicated that, except for ASD1 in Citra, FL, the improvement in marketable tomato fruit yield in ASD treatments was significant enough to obtain a positive net return compared with CSF. That is, adopting ASD treatments might bring farmers more profits, although we failed to obtain a consistent result between the two

locations, prevented the overall conclusion that applying more molasses would result in a greater net return.

It should be noted that the cost of implementing the required Fumigant Management Plan, which specifies that workers be trained in fumigant application and potential emissions monitored, was not considered in estimating the cost of CSF (Talley and Werling, 2016). Neither did we include the costs of worker protection equipment replacement (e.g., the replacement of filters in respirators) in our calculation of total costs. In addition, because ASD treatments also provide crops with nutrients, a fertilization optimization program for ASD may reduce production costs. Therefore, if accounting for all the preceding factors, the differences in costs between CSF and ASD application may not be as great as those presented here.

In conducting partial budget analysis to compare different production practices/technologies such as grafting and nongrafting in tomato production, Djidonou et al. (2013) found that grafting generally incurred more added costs compared with nongrafting, but it also generated significant added returns. The added returns of grafting covered the additional costs of grafting. Our partial budget analysis resulted in a similar conclusion in that the net return of ASD treatments were positive in most cases despite their added costs compared with CSF.

SENSITIVITY AND BREAKEVEN ANALYSIS. Information provided in Tables 6 and 7 illustrate how net returns associated with ASD treatments and the differences between ASD treatments and CSF change with molasses price and tomato price in Immokalee, FL, and Citra, FL, respectively. At the breakeven molasses price, ASD and CSF led to the same net return. Theoretically, these breakeven prices represent the maximum molasses costs at which growers will adopt ASD. The breakeven molasses prices for both ASD0.5 and ASD1 were all higher than the price of molasses used (i.e., \$0.63/gal) in both locations, except for one condition in Citra, FL, between ASD1 and CSF, in which case the breakeven prices were all negative. The negative breakeven molasses prices indicate that ASD1 was less profitable than CSF in Citra, FL. A higher positive breakeven price (than \$0.63/gal) indicates that growers would incur an economic gain if they switch from CSF to ASD at the current or even higher molasses price. In Citra, FL (Table 7), ASD0.5 was better than CSF and ASD1 because it generated a higher net return and its breakeven prices were, on average, the highest under all the conditions (e.g., a breakeven molasses price equal to \$5.77/gal when the tomato price was \$18.92). All of these results led to the conclusion that ASD treatments, particularly when using the smaller quantity of molasses, would bring growers a higher profit than using CSF, even at a higher molasses price.

Data provided in Table 8 illustrate how the net returns of treatments and differences between treatments change with tomato price and tomato yield in Immokalee, FL. Holding tomato yield constant, increasing

tomato prices made ASD treatments more advantageous compared with CSF when tomato yield of the ASD treatment was higher than that of CSF. When tomato yield of ASD treatments was low, CSF treatments would generate more profits than ASD treatments. Although the average yield for open-field tomato production in Florida is 1344 25-lb cartons per acre (USDA, 2017), the breakeven tomato yields were all between 1600 and 2000 cartons/acre for ASD0.5 and ASD1, with the average breakeven yield of ASD0.5 being lower than ASD1. The results of the same sensitivity analysis in Citra, FL, are presented in Table 9. Similar to Immokalee, FL, when tomato yield from ASD treatment was high, both ASD0.5 and ASD1 became increasingly more profitable than CSF as tomato price increased. The breakeven tomato yields in Citra, FL, were generally higher than in Immokalee, FL. Because material prices, weather conditions, and yields are always fluctuating, these results offer growers varied scenarios of net returns based on different conditions.

Djidonou et al. (2013) and Barrett et al. (2012) also found that the net return difference between grafting and nongrafting became more substantial as tomato price increased. Similar patterns were observed in this data set in that the relative net profits of ASD treatments compared with CSF were very sensitive to tomato price. Higher tomato price would make ASD treatments more attractive to farmers, but ASD treatments must result in yields that meet the established threshold to be profitable compared with CSF.

Conclusions

Economic analysis was conducted using the field application results of three soil treatment methods that included two ASD treatments with different application rates of molasses and CPL compared with CSF in terms of their economic profitability for growers. The economic analysis in this study focused on the differences between CSF and ASD treatments in land preparation cost, gross return, and net return. The costs of molasses and additional labor were the main factors leading to increased land preparation costs associated with ASD treatments. ASD

treatments required higher material and labor costs in land preparation, whereas increasing gross returns if the tomato yield improvement resulting from ASD offset the increased cost. In Immokalee, FL, both ASD treatments generated higher net returns than CSF.

Despite the higher cost associated with ASD application, ASD may be a more profitable soil disinfestation method for farmers than CSF, potentially resulting in greater economic net returns. The advantages of using ASD with respect to soil and environmental impacts and movement toward long-term sustainability might provide even more incentive for ASD adoption. As research continues to seek solutions to optimize ASD treatments and lower the associated cost and improved adaptation to site-specific conditions, the profitability of ASD could potentially increase. Results of the sensitivity analysis demonstrate that even if molasses prices increase, ASD treatments could still have advantages over CSF due to the increase in tomato yield. Although there are no direct comparisons, these results may be applicable to organic tomato production in Florida, which prohibits the use of CSF for pest control, and returns may be higher due to price premiums associated with organic commodities. Finally, our economic analysis is based on the operation of a representative grower and data collected from the experimental stations. The economic benefit and cost will nevertheless be affected by the farm size. For large farms, the economic benefit of ASD would be more significant because the unit cost of ASD application would decrease because of the economy of scale. Future research could be conducted on different sized farms to determine the impact of farm size on the economic cost and benefit of ASD for tomato production in Florida. In addition, opportunities for improved mechanization and combining steps in the ASD application process may further decrease labor costs in the future.

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