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Economic Viability of Weed Management Strategies in High-Tunnel Tomato

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Economic Viability of Weed Management Strategies in High-Tunnel Tomato

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Abstract

Cost-effective weed suppression is an important consideration for tomato growers. Growers often choose methods which minimize hand labor, as hand weeding can be prohibitively expensive. This project determined economic viability of high tunnel tomatoes treated with several methods of weed control, both organic and chemical. These methods included: 2-week hand weeding, 1-week hand weeding, preemergent, straw, landscape fabric, and untreated weedy control plots. These treatments were applied to randomized blocks in a high-tunnel. Weeding, planting, and harvest were all timed to determine labor and material costs of weed management strategy implementation. After harvest, marketable yield was weighed to determine revenue. Partial profit was determined through sensitivity analysis. Means separation analysis, a payoff matrix, and distribution curves were created to compare the partial profit between plots. The preemergent generally outperformed all other treatments, while straw and weedy plots tended to have the lowest partial profit. Based on distributions, tomatoes treated with landscape fabric, which had the second highest partial profit, would have to be sold at a 40 cent/kilo premium to compete with preemergent treated plots. No labor cost scenario allowed organic strategies to compete with preemergent. This is relevant to growers in that the results can be used to adjust their weed management practices based on their available labor resources, yield expectations, and market price expectations to get the best partial profit.

Introduction

Background and Need

In the agricultural field, weeds can cause damage to specialty crop yields. Many previous studies have investigated the harmful effects of weed interference on tomato production (Chaudhari et al., 2016; Chaudhari et al., 2017; Ghosheh et al., 2010; Jennings 2010). Developing strategies to minimize weed interference is a crucial part of managing crop health and ensuring an economically viable yield.

When creating a weed management plan in specialty crops, individuals must take labor cost into account, as management needs differ based on available labor resources and profitability. In market garden production, activities such as transplanting, harvest, and weeding must be conducted by hand. Many production practices are implemented to minimize the labor hours required for weeding, including those examined in this research: landscape fabric, straw mulch, and application of preemergent herbicides.

Production practices can also depend on personal needs and production philosophies of each grower. An example of this is the debate regarding certified organic strategies, which emphasize management through natural ecological systems, and conventional strategies, which rely on chemical application such as herbicides (Bond and Grundy, 2001). In this study, use of a preemergent herbicide represents a conventional strategy, while the rest of the strategies are organic. It is important to note that both strategies could work within a conventional production system, only that the use of synthetic preemergent herbicides is specifically disallowed in

certified organic production, as weeds must be controlled mechanically, physically, or biologically (USDA AMS). Taking labor and production practices into account, one of the most important considerations for many growers is profitability. This study investigates the economic costs and returns of several weed management practices in high-tunnel tomato production.

Tomato growers can use the results of this research to determine which weed management techniques are the most beneficial based on their individual needs and available resources. Additionally, the data collected will create a baseline for similar future research to be conducted, as the methodology is replicable for application in future projects.

Problem statement

A need exists to conduct economic analysis comparing the partial profitability of high-tunnel tomatoes treated with organic weed management strategies, such as straw mulch, landscape fabric, and hand weeding, to conventional weed control strategies involving preemergent herbicide.

Purpose statement

The purpose of this research was to assess the economic viability of high-tunnel tomato plots treated with representative weed management strategies including landscape fabric, straw mulch, preemergent herbicides, weekly and biweekly (every two weeks) hand weeding, and a control of no weed management. Using a partial budgeting analysis, wherein only differences in revenue and cost are compared across weed management systems, we identify the most profitable and least risky alternative. The labor, material, and equipment costs of implementing

each weed management strategy, as well as revenue differences associated with yields for each strategy, were compared across production systems to evaluate relative profitability differences.

Objectives

- 1) Assess partial returns of tomato production, accounting for yield, crop price and weed management costs of the following weed management treatments:
landscape fabric plus hand weeding, straw mulch plus hand weeding, preemergent herbicide plus hand weeding, weekly hand weeding in absence of other weed prevention, hand weeding every two weeks in absence of other weed prevention, and no weed control.
- 2) Compare the partial returns of each treatment to determine which strategy was most profitable under simulated labor cost and tomato market value conditions using triangular probability density functions fitted to empirically observed data on yield, time to weed, plant and harvest.

Literature Review

The literature used to develop this project examined factors influencing specialty crop profitability, observations of weed control strategy characteristics in past studies on specialty crop production, and the significance of the current investigation into organic weed control labor cost in comparison to costs involved with conventional practices involving herbicide use. Labor cost has increased over time, as have production costs (USDA ERS), and consequently, a price premium for organic production is expected. The literature suggested potential future research

examining the effects of locational and temporal factors of weed management strategies on profitability.

High-Tunnel Tomato Production in Arkansas

Tomatoes require specific conditions to thrive and produce sufficient yield to make their cultivation worthwhile for a producer. According to the University of Arkansas Division of Agriculture website, tomatoes thrive in warm, sunny areas with well-drained, moist loam soil. Arkansas summer conditions are adequate for tomato planting. High tunnels, plastic covered frames used as a protective cultivation method for housing plants, are used to further idealize the tomatoes growing conditions (Lamont, 2009). High-tunnels can be used to expand the growing season of tomatoes, increase the temperature around them, and protect them from weather and pests (Reeve and Drost, 2012). High tunnels reduce disease pressure and increase marketable yield of tomatoes (Rogers and Wszelaki, 2012).

Factors Influencing Profitability

Economic analysis of specialty crop production is dependent on crop performance, local market prices, and expenses associated with specific management practices. Market prices of specialty crops change over time, fluctuating due to changes in supply and demand such as imports from other countries, weather changes, and available land for crop production (Guan et al., 2018).

Labor cost changes depending on production strategy, weather, type of crop, and other factors (Galinato and Miles, 2013). Regional variation is another factor in economic viability. Economic research from other states and countries has limited applicability in Arkansas, based

on differing climatic conditions and differences in regional wholesale or fresh market pricing. Frequent reassessment of cost versus benefit is necessary to determine which strategy is most economically viable at a given time, with given conditions.

In this project, production was limited to one crop, and the groups were grown concurrently in the same high tunnel and under the same conditions with the same water and soil. Thus, an investigation on the weed suppression and economic viability of several common management practices in tomato production can be of immediate utility for growers in Arkansas.

Growers can seek out weed management decision models, which are programs designed to assist in the selection of weed management strategies, to make management decisions (Colas et al, 2020). These models are often developed from weed management research data (Korres et al., 2019). Models must be updated frequently to account for the changing nature of the market and available technologies (Wiles, 2004). With changing conditions, it is important to generate new research on the costs and benefits of various weed management strategies.

Observed Effects of Weed Control Strategies

Effective weed management strategies must take environmental factors of the specialty crop into account, such as habitat, soil characteristics, climate, growth cycle and growth habit (Smeda & Weston, 2017). Weed management strategies are chosen with the goal of minimizing negative interference on production while maximizing yield value and weed suppression (Smeda & Weston, 2017). Hand weeding, straw mulch, landscape fabric, and preemergent herbicides each have unique characteristics that affect material and labor cost and impact yield.

Hand weeding has been shown to improve plant growth, yield, and yield quality in tomatoes while reducing weed density (Ijaz et al., 2017). In a study on tomatoes, hand weeding was more successful in decreasing weed density than preemergent herbicides or mulching (Bakht and Khan, 2014). However, hand weeding is known to have a higher labor cost than other management strategies (Deese, 2010). According to one study, it took researchers approximately two hours to hand-weed a hectare of tomatoes (Kennedy, 2018). Because of the labor cost, despite its effectiveness in weed removal and positive effects on yield, hand weeding does not necessarily guarantee the highest net profitability (Daramola et al., 2020).

Organic mulches improve growth, yield, and quality of yield (Sinkevičienė et al., 2009). Straw mulch has been observed to trap soil moisture, improving crop growth (Tindall et al., 1991). Straw mulch is preferable to other types of mulch, as past studies comparing mulches have observed higher yields from straw mulch than plastic, possibly due to the greater soil infiltration, lower surface evaporation, and lower soil temperature provided by the straw application in high temperature environments (Tindall et al., 1991). Straw mulching is known to enhance microbial activity and water availability for microbes (Tu et al., 2006). Because of straw mulch's water retentive characteristics, it reduces the water necessary for a healthy plant, reducing material costs for growers (Biswas et al., 2015). Soil erosion is reduced by straw mulch as well (Döring et al., 2005). Past studies have found that mulch requires a concentrated early season workload of labor, because mulching an area takes time (Brown and Gallandt, 2019). However, mulching also reduces labor later in the season due to its weed-suppressive nature (Brown and Gallandt, 2019).

Landscape fabric requires relatively little labor to install, but more labor to plant and remove (Strader and Dawson, 2018). It is designed so that water can penetrate and get to the

plants while excluding light to prevent weed growth under the fabric (Hammermeister, 2016). Landscape fabric can last for several years, meaning it does not need frequent replacement if used over time and the material costs after initial application are largely fabric repair costs. (Ingels et al., 2009). Overall, landscape fabric has a positive effect on growth and yield of tomatoes and other specialty crops.

Preemergent herbicides are designed to kill germinating seeds and work best in areas with adequate moisture (Bakht and Khan, 2014). *S*-metolachlor, the preemergent herbicide used in this project, has been observed to require less labor than hand weeding (Zewdie and Yohannes, 2019). Application of *S*-metolachlor has been shown in past studies to improve tomato yield, though not as much as hand weeding (Bakht and Khan, 2014).

Significance of Conventional versus Organic Systems

There is debate regarding economic viability of conventional versus organic systems (Posner et al., 2008). Modern agriculture has greatly contributed to nonpoint source pollution, which has led to growers adopting organic systems (Mateo-Sagasta et al., 2017). Organic agriculture is largely considered more sustainable than conventional systems, but less economically viable because of the yield gap (De Ponti et al., 2012). However, if growers use the USDA market standard for Organic product, the product could be more attractive to wholesalers and could be sold at a premium (USDA AMS). People may prefer organically treated products for lifestyle or environmental reasons, and past studies show that organic tomato premiums average around 22% above conventional prices (Zhang, Feng, et al, 2009). Productivity, yield quality, and labor cost are all considerations of economic viability. As labor cost conditions and yield market value conditions change, and improved methods of weed management are

developed, it is important to continue generating new research to determine which weed management systems are the most economically viable for growers.

Research Gaps

Assessments of weed control strategies have been conducted in past studies, both for organic weed control and conventional systems. However, little work has been done comparing the two. The only relevant economic analysis of organic versus conventional weed control systems was conducted as a comparison of the performance of herbicide regimes compared to fumigation with methyl bromide (Devkota et al., 2013).

Past researchers have noted that using weed control only during the critical period of a crop, meaning the time during which weed control is necessary to avoid yield loss, can lead to an increased weed seedbank that affects labor costs and yield in the following years (Brown and Gallandt, 2019). Norsworthy et al. (2014) suggests a zero-tolerance threshold for weeds to prevent weed increase over time. The research conducted in the current study is limited in that it evaluated the economic viability of weed management on tomatoes grown in high tunnels over a single season in Arkansas.

Future research could expand on this project by investigating the impact of each weed management strategy over several years, or several different areas. Because regional and temporal differences drastically affect yield, yield market value, and labor cost, future research could involve a similar experiment design to this research but on a larger scale examining performance of different management systems over time, across different regions, or worldwide. As new farmers are trained through programs like the Center for Arkansas Farms and Food, it is

critical that the economic implications of different management strategies are investigated and shared in a timely manner.

Methods and Materials

The objective of this research was to assess the economic viability of several weed control strategies for high-tunnel tomatoes: Landscape fabric, preemergent herbicide, hand weeding, and straw mulch. Each method was used alongside hand weeding to ensure effective weed suppression. Plots with no passive weed management and no active weeding served as controls. Visual assessments of weed control were collected in each plot every two weeks over the course of the season. Following visual ratings, all plots were hand-weeded at the same two-week interval. Payoff matrices and cumulative probability density functions, generated from fitted distributions of empirical data were created to compare market value from yield versus labor and material costs in several labor cost and yield market value scenarios to determine which treatment was most profitable or least risky. At the same time, the comparison across organic and conventional weed management strategies allowed calculation of a necessary market premium for choosing organic methods.

Research Design and Data Collection

This study was conducted using a quantitative experimental research design, which tests the dependent variables as a function of the independent variable (Cash, 2018). The dependent variable, which was the partial profitability of plots treated with each type of weed control based on labor and material cost versus market value of tomatoes, depends on the independent variable,

which is the type of weed control used on the plots. This design allowed for data collection through researcher observation in the field, and analysis (Cash, 2018).

Celebrity variety tomato was sown in 72-cell until plants reached 2 to 3 true leaf stage. Over the next three days, plants were then taken outside for several hours in the middle of each day to harden off plants prior to transplanting. Tomato seedlings were transplanted into a high-tunnel structure into 0.762-m wide preformed beds at the Milo J Shult Research and Extension Center in Fayetteville, AR. The preemergent herbicide used was *S*-metolachlor (Dual Magnum, Syngenta) applied at 1.68 kg active ingredient per hectare, using a CO₂ powered backpack sprayer calibrated to deliver 75.69 liters per acre. Landscape fabric and straw mulch (4.08 kgs per plot) were applied to beds immediately after bed formation. Treatments were assigned to 8 plant plots, with each plant spaced at 0.46 m. Experimental units for the project were 3.66-m plots with 8 tomato plants. All treatments were replicated 4 times and arranged in a randomized complete block design according to any known variation in the site. alleys (0.91) were spaced between plots in each bed.

Data were collected on cumulative time spent for dedicated hand-weeding each plot to keep a site free of weeds under each management practice. Material and labor cost for spreading mulch, laying fabric, and preplant incorporation of chemical weed control were tracked. Data were also collected on visual ratings of weed control, assessed as percent coverage, every 2 weeks. Alleys between plots were also hand weeded, but this was not timed.

In mid-October through early November, four harvests were conducted and timed. Two people stood on either side of the plot and picked all visible ripe tomatoes from each plot. The tomatoes were sorted as marketable or cull based on USDA market standards of size and

appearance (USDA 2022). Tomatoes that were visibly smaller, extremely discolored, rotting, showing signs of worms or deficiencies, were marked as cull, while ripe, healthy tomatoes were marked as marketable. Mature tomatoes were counted and weighed in crates on a scale to determine the marketable fruit number and weight in pounds per plot.

The labor and material costs of implementing the management strategies were compared against market value of the tomato harvest in a partial budget economic analysis to determine which weed management strategy had the highest partial returns. To assess relative profitability, comparisons of partial returns and sensitivity analysis allowed determination of the most profitable production method. An area of interest was how labor cost and yield market value could affect relative profitability, and what scenarios could change the results of the study.

At season's end, cumulative hours spent for dedicated hand-weeding were recorded for each plot to quantify the labor costs required for keeping each site free of weeds under each management practice. The overall costs of materials, labor, and equipment that differed across production systems were compared to the gross income of each treatment to calculate the relative profitability of each strategy for growers.

Sensitivity analysis on wage rates, key input costs and tomato sale prices were conducted to give nuance to the results and make the results relevant to a wider group of growers. It should be noted that the tomatoes in this experiment were harvested later than the usual Arkansas growing season, as the high-tunnel allowed for an extended season.

Following execution in the field, analysis of variance (ANOVA) was conducted in SAS using the GLIMMIX procedure to compare response variables, and means separation was conducted according to Tukey's Honest Significant Difference at a 0.05 significance level. Weed

management strategy was treated as a fixed effect, and rep was treated as a random effect. USDA standard market values of the harvested tomatoes were used to calculate the potential gross and net revenues associated with each practice, accounting for expenses associated with each treatment and time spent weeding in each treatment. To assess relative profitability, comparisons of partial returns (tomato yield * price – labor, equipment and material costs that differ across treatments) allowed determination of the most profitable production method (the one with highest partial returns) as well as sensitivity analysis. One area of interest was how labor cost/hour may affect relative profitability.

Rigor

An important part of quantitative, true-experimental research is ensuring results are valid and reliable. Validity and reliability were achieved through the experimental design and results. Rigor was addressed through internal validity, external validity, reliability, and objectivity in this study.

Internal Validity

Internal validity is the establishment of a causal relationship between treatments and outcome (Slack and Draugalis, 2001). Internal validity was established through a randomized complete block design, a design wherein experimental units were divided into blocks to reduce unexplained variation and confounding variables (Addelman, 1969). The tomato variety used was a common and representative variety that appropriately reflects growth characteristics of tomatoes Arkansas growers would plant. Plots of eight plants were determined to be sufficiently large to capture treatment effects with appropriate statistical power. By keeping the plants of each group in the same conditions, a more accurate sense of the treatment effects was achieved.

External Validity

This study sought external validity, the ability to apply the findings to a larger population or general context, by taking notes during field observations and transcribing them accurately so that the information was replicable under identical conditions (Lucas, 2003). The data collection section addresses the methods used step-by-step so that they are repeatable. The research is generalizable to high-tunnel tomato plots on other farms with similar weed management needs under similar climatic conditions. External validity is ensured through the use of replicates, which are experimental runs with the same factors (Casella, 2010). All treatments were replicated four times. Statistical confidence intervals, which are ranges of values used to gauge effects of sampling variation on data precision, were used in analysis of the results to ensure reasonable accuracy in statements made about the findings of the research (Newcombe, 2012). By using a randomized block design, the study was made generalizable to any tomato plants in the same conditions as those in the experiment (Ferguson, 2004).

Reliability

Reliability is the measure of accuracy which indicates that results are unbiased and error-free (Maines and Wahlen, 2006). Reliability was addressed in this research by including only a population of tomatoes that were reasonably similar in environment, having all grown in the same season, year, and high-tunnel conditions. Tomatoes were placed in a randomized complete block design to decrease the likelihood of confounding variables altering the results. Measures of reliability were used during analysis in the GLIMMIX SAS procedure.

Results

Wage data were taken from NASS ERS quarterly reports and inflation was accounted for to create the average real prices over a 5-year period in the Delta region, which includes Arkansas (USDA ERS). Tomato price data were taken from 2021 USDA market reports from Arkansas (USDA, 2021). Since tomatoes can be shipped in multiple types of packaging that carry different weights, the market data were converted into a standard \$/kg format to determine pricing per weight (USDA). Triangular probability density functions were fitted to these values on the basis of acceptable Akaike information criterion (AIC). The mean wage value, \$13.40/hr, was multiplied by the harvest time, planting time, and weeding labor time to determine the average labor cost, and the mean tomato market price value, \$1.44/kg, was multiplied by the yield to determine the mean tomato market price value. It should be noted that while sizes of individual tomatoes are checked by some growers, they were not taken into account in this experiment (USDA 2022). Dual Magnum preemergent herbicide, bought in a 9.45-liter jug, averaged \$0.0125/plot. Straw averaged \$6.25/plot with about 4.08 kg/plot, and landscape fabric with staples averaged \$4.95/plot in 3.66 m x 0.762 m plots and approximately 30 staples/plot.

The payoff matrix partial profit values came from the following equation: market yield x price per kg fruit – weeding and harvest labor time x labor cost – planting and material cost of landscape fabric, preemergent herbicide, and straw mulch. Regret was calculated as the difference between the highest partial return strategy and the alternative in question to assess which production strategy demonstrated the least regret across trial replications to determine which treatment consistently had the highest partial return (Table 1).

The payoff matrix indicated that in an average labor cost and average tomato market value scenario, preemergent herbicide treated plots achieved the highest partial profit (Table 1).

For maximum of the minimums (maximin), a situation where a grower chooses the management strategy with the highest of the worst outcomes, preemergent herbicide treated plots had the highest partial return out of the worst scenarios and would be the most viable choice. For maximum of the maximums (maximax), wherein growers choose the strategy with the highest partial returns, preemergent herbicide treated plots also have the highest partial returns. For expected value (exp. value), wherein growers choose the strategy with the highest average of uncertain outcomes (treatment replications), preemergent herbicide treated plots had the highest average. For minimum average regret, wherein the grower chooses the strategy with the lowest average regret across uncertain outcomes, preemergent herbicide treated plots had the lowest average regret. The outcomes considered the most desirable in each of these situations are in bold face beneath the table (Table 1).

Triangular probability density functions (TPDF) were fitted to empirical observations involving planting, weeding and harvesting labor as well as yield using the @Risk Excel add-in program. See Appendix Table 1 with fitted distribution parameters. The TPDF was chosen as it provided the highest AIC statistic or was near the top when fitting among other probability density functions such as the beta, general, uniform, etc. Additionally, the TPDF was chosen for its ease of interpretation as only the minimum, maximum and mode need to be specified to describe the probability density function (PDF). To determine the cumulative probability function (CDF) of partial returns among production strategies, @Risk uses the fitted PDFs to randomly select observations from each input PDF to calculate partial returns over 10,000 iterations. In this case, fitted additional input TPDFs were for the tomato market value, using a history of observed market prices, and a TPDF for hourly wage rates, again using a history of observed wage rates (*Market News USDA NASS*). The CDF of partial returns to production now

show the likelihood of achieving a particular level of partial return. A steeper CDF curve implies less risk in the sense that the range of profitability outcomes is smaller. A CDF curve position further to the right implies a greater probability of achieving a desirable partial return than a CDF that is further to the left. The most desirable outcome would be a situation with the least risk (steepest CDF), and one positioned furthest to the right at the 50% percentile of partial return observations, assuming data are plotted from least profitable at the left to most profitable at the right.

To assess which of the production systems had the highest partial returns (CDF furthest to the right) and/or was least risky (steepest CDF), the simulated CDFs of planting costs, weeding labor, harvest labor, yield and harvest revenue were also plotted to showcase which of these four factors had the largest impact on partial return differences. Since all of these curves involve more than one TPDF, their combination creates CDFs that take on the familiar shape of a normal PDF although typically skewed.

The preemergent herbicide treated plots had the highest partial profit, with the 50th percentile at \$15.79/plot (Figure 1). Fabric was the second-best option, with a similar distribution curve to the weedy plots, but steeper, meaning fabric was less risky than preemergent. The revenue curves show that preemergent herbicide outperforms the other treatments, and fabric has the second highest revenue (Figure 2).

Preemergent and weedy plots have the greatest harvest labor costs because the preemergent plots had a large yield, and the weedy plots, despite a smaller yield, were difficult to harvest given the volume of weeds growing around the tomatoes. Fabric is a close third behind these two curves (Figure 3). The weeding labor cost of the weedy plots was the lowest because they were un-weeded, thus there was no curve for these plots on the graph. Fabric were the

second lowest, followed by preemergent and straw. The hand-weeded plots had the highest labor cost (Figure 4).

Fabric-treated plots had the greatest planting and material costs. The hand-weeded plots did not require material, thus their costs were lower. The hand-weeded, weedy, and preemergent herbicide treated plots all averaged around 50 cents for material and planting costs per plot (Figure 5). Preemergent herbicide treated plots had the greatest yield, followed by fabric treated plots. Weedy plots had the smallest yield (Figure 6).

To examine potential scenarios that could affect these results and potentially make organic methods more economically viable than preemergent herbicide use, a TPDF for an organic price premium was created to see how much of a premium fruit from fabric-treated plots, with the second highest partial profit, would need to be sold at to achieve the same partial profits as preemergent herbicide-treated plots on average. It was determined that fabric-treated tomatoes would need to be sold at a 40 cent/kg premium to compete, with profit curves overlapping around the 57th percentile at \$17.67/plot (Figure 7). However, the preemergent herbicide treatment was less risky with a steeper curve, so even in this scenario it was still the more economically sound option of the two.

A second curve was created to display the revenue in this scenario. When a 40-cent organic premium/kg was added to fabric-treated plots, the revenue for preemergent herbicide-treated plots at the 50th percentile was \$21.36/plot and the fabric-treated plots revenue was \$23.39/plot (Figure 8). At the overlapping point, 57th percentile, the preemergent herbicide-treated plot revenue was \$23.20/plot and the fabric-treated revenue was \$25.57/plot.

There was an attempt to create curves to find a scenario in which the fabric-treated plots labor cost was low enough to compete with preemergent herbicide-treated plots partial profit, but it was not possible to create this curve, because there was no scenario where this was possible. Even if the fabric-treated plots had a \$0 labor cost the fabric-treated plots partial profit could not compete with the preemergent herbicide-treated plots.

There was also an attempt to create curves to determine how much preemergent herbicide material cost would have to increase for it to have less partial profit than the organic strategies. As it turns out, preemergent herbicide material and planting cost would have to increase 480-fold to be outperformed by landscape fabric.

Means separation analysis results for labor time at various stages of the project indicated that preemergent herbicide, straw mulch, and landscape fabric are statistically different in the preparation stage, while the rest of the treatments do not require preparation and thus have no values in that column. Landscape fabric is the only statistically different value in terms of planting time, while the other values are similar to each other. Fabric-treated plots took significantly less time than the other plots for weeding, given that few weeds could survive under the fabric. Hand-weeded plots required the most maintenance while weedy required the least. Weedy plots and 1-week hand-weeded plots had the lowest harvest total hours, which included values from all harvests. These were statistically different from the preemergent herbicide-treated plots, which had the highest harvest labor time totals. For the green harvest, where remaining green tomatoes were harvested prior to ripeness at the end of the trial, the 2-week hand-weeded and preemergent herbicide treated plots took the longest, and the weedy plots took the shortest number of hours. In total, the weedy plots took the shortest time to plant, maintain,

weed, and harvest, and the hand-weeded plots took the longest. In the individual harvests, the times were statistically indistinguishable for all treatments (Table 2).

Marketable and cull yield were assessed through means separation analysis (Table 3). Cull yield, cull fruit size, and cull fruit count are statistically indistinguishable between treatments, as the P value is greater than 0.05. In categories of marketable yield and marketable fruit size, weedy control plot values were smaller, meaning they had less fruit.

Weed coverage percentage was assessed through visual ratings throughout the project, and means separation showed that beginning of season, plots had not yet been weeded, early emerging weeds were able to germinate. Interestingly, weedy plots had less weeds initially than other treatments (Table 4). As time progressed at different weekly intervals, it quickly became apparent that weedy plots had excessive weed coverage, with very little difference among the other weed treatments. Weed coverage never exceeded 15% of the plot, even in 2-week hand-weeded plots. Plots were generally similar in mean weed cover. Common weeds were carpetweed, thistle, morning glory, oxalis, clover, carpetweed, and various grasses (data not shown).

Conclusions

The preemergent herbicide-treated plots had higher partial profitability than organic treatments in all scenarios explored here. The preemergent herbicide is relatively inexpensive and generates more revenue. Landscape fabric-treated plots were the second-most profitable overall and could compete with preemergent herbicide-treated plots when fruit was sold at a 40 cent/kg premium near the 50th percentile, though the risk was still greater for fabric-treated plots. The topic of consumer horticulture and cost-benefit analysis is timely and relevant for Arkansas

growers, as they can use the results to determine which weed management practices are economically viable based on their budgets and needs. These results showcase some of the factors influencing the profitability of weed management strategies. However, despite the clear economic advantage of preemergent herbicide, economic considerations are not the only considerations of agricultural operations. A population of growers exists that choose organic strategies for production philosophy reasons. The information presented here, while not the only relevant consideration for growers, can be used by growers to inform them of the potential barriers and benefits to the weed management strategies explored in this project, so they can make informed decisions.

Tables and Figures

Table 1. Payoff Matrix of partial returns to tomato production across six different weed management strategies with controllable action choice identified using maximin, maximax, expected value and minimum average regret rules.

Payoff Matrix		Controllable Action Outcomes in \$/plot											
Weed Management Strategies		Preemergent ^a		Weedy		2 Week		Straw		1 Week		Fabric	
Uncontrollable State of Nature	row 1	0.00 ^c	1.94	6.62	10.02	14.36	11.20	17.40 ^b	15.46	10.78	7.38	3.04	6.20
	row 2	3.40	0.00	6.66	8.42	8.28	5.84	11.13	14.52	7.86	6.10	6.24	8.68
	row 3	3.49	12.69	7.25	5.76	2.96	0.00	13.26	4.05	9.49	10.99	13.78	16.74
	row 4	0.00	14.31	6.56	2.92	8.05	7.76	16.52	2.21	9.96	13.60	8.48	8.77
	Maximin ^d	11.13	2.21	7.86	6.10	3.04	6.20	17.40	15.46	10.78	13.60	13.78	16.74
	Maximax	17.40	15.46	10.78	13.60	13.78	16.74	14.58	9.06	9.53	9.52	7.88	10.10
	Exp. Value	14.58	9.06	9.53	9.52	7.88	10.10	1.72	7.24	6.77	6.78	8.41	6.20
	Min. Avg. Regret	1.72	7.24	6.77	6.78	8.41	6.20						

- Notes:
- ^a Preemergent = preemergent herbicide, Weedy = un-weeded control, 2wk = hand-weeded every 2 wk, 1 wk = weekly hand-weeded Straw = using straw mulch, Fabric = using landscape fabric. All strategies involved hand-weeding at a 2 wk interval except 1 wk and the weedy control.
 - ^b Observed average partial returns calculated as tomato yield in kg/plot x average tomato price in \$/kg - planting cost for labor and materials in \$/plot less the sum of weeding and harvesting time in sec./plot x wage rate in \$/sec.
 - ^c Dollar regret of choosing a controllable action that experienced less than the max. observed partial return for a particular state of nature.

- ^d Maximin = choosing the weed management strategy with the highest of worst outcomes. The worst outcome is shown for each strategy. Maximax = choosing the weed management strategy that had the highest partial return. The best outcome is shown for each strategy. Exp. Value = choosing the strategy with the highest average of uncertain outcomes. The average partial return is shown for each strategy. Min. Regret = choosing the strategy with the lowest average regret across uncertain outcomes. The average regret is shown for each strategy. The optimal strategy is identified for each decision rule in the bottom four rows in bold font.

Table 2. Means Separation Analysis for Time for Weed Management Strategy Implementation.

Treatments	Prep	Planting	Weeding	Maintenance	Harvest Totals	Green	Total	Harvest 1	Harvest 2	Harvest 3	Harvest 4
hr ha ⁻¹											
1 wk Hand	-	32.42 b	810.28 a	890.39 a	258.89 b	116 ab	1149 a	25.8	38.00	50.83	27.4
2 wk Hand	-	29.09 b	764.07 ab	835.96 a	309.20 ab	149 a	1145 a	31.14	45.22	51.08	32.27
Preemergent	1.73 c	31.61 b	502.44 ab	582.28 ab	362.16 a	151 a	944 ab	31.41	63.16	80.24	35.51
Straw	36.74 b	27.53 b	451.73 b	556.51 ab	280.07 ab	118 ab	836 ab	26.04	52.71	57.67	24.66
Fabric	130.69 a	58.99 a	62.67 c	339.10 bc	317.18 ab	135 ab	656 bc	36.13	57.06	63.90	25.03
Weedy	-	31.61 b	-	78.11 c	260.13 b	85 b	338 c	36.87	38.13	68.77	30.64
P-value	<.0001	0.0089	0.0002	<.0001	0.0331	0.0117	<.0001	0.2938	0.1100	0.5040	0.5528

Notes: Areas marked with a “-“ have no data for the means separation analysis because no time was expended for labor. These cells indicate a labor time of 0 hours per hectare. 1 wk Hand refers to weekly hand-weeded treatments. 2 wk Hand refers to bi-weekly hand-weeded treatments. Prep refers to preparation. Green refers to green harvest, wherein remaining unripe green tomatoes were harvested at the conclusion of the trial.

Table 3. Means Separation Analysis of Yield Values.

Treatments	Marketable Fruit Count	Cull Fruit Count	Marketable Yield	Cull Yield	Marketable Fruit Size	Cull Fruit Size
	fruit ha ⁻¹		kg ha ⁻¹		kg fruit ⁻¹	
1 wk Hand	320,675 ab	21,080	65,168 ab	3,444	0.22 ab	0.22
2 wk Hand	389,294 a	15,248	79,701 a	2,626	0.24 ab	0.24
Preemergent	380,324 a	19,733	75,859 a	3,220	0.32 a	0.23
Straw	347,135 a	14,801	71,027 a	1,981	0.23 ab	0.21
Fabric	357,002 a	25,115	70,034 a	3,409	0.21 ab	0.20
Weedy	178,501 b	12,110	36,568 b	1,542	0.20 b	0.21
P-value	0.0059	0.4881	0.0096	0.4339	0.0371	0.0858

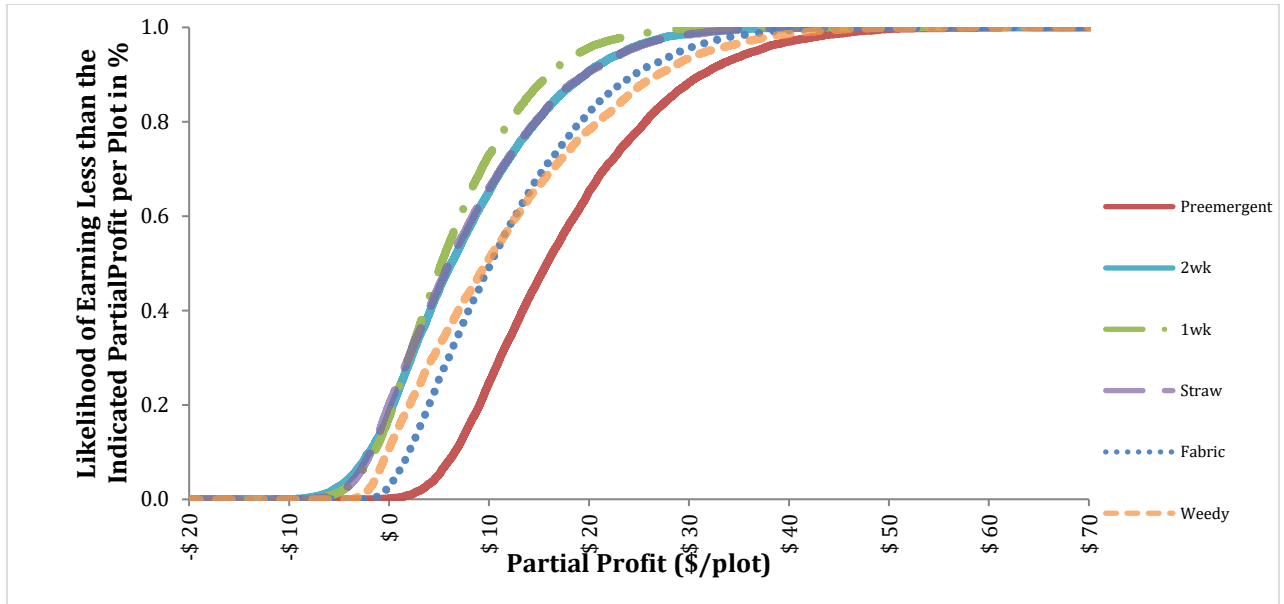
Notes: 1 wk Hand refers to weekly hand-weeded treatments. 2 wk Hand refers to bi-weekly hand-weeded treatments.

Table 4. Means Separation Analysis on Weed Coverage in Percent.

Treatments	Aug 11	Aug 18	Aug 25	Sept 01	Sept 08	Sept 15	Sept 22	Sept 29	Oct 06
	%								
1 wk Hand	3.25 ab	3.75 b	2.75 bc	3.50 b	4.50 b	2.25 bc	3.00 bc	2.5 bc	2.5 cd
2 wk Hand	25.25 a	4.00 b	14.50 b	5.75 b	9.50 b	3.00 bc	6.25 b	4 b	6.5 b
Preemergent	7.00 ab	2.50 b	8.25 bc	6.00 b	5.00 b	2.50 bc	3.75 bc	2 bc	4.7 bc
Straw	20.00 ab	2.50 b	2.75 bc	4.25 b	8.25 b	3.50 b	5.25 b	2 bc	3.0 bcd
Fabric	1.00 b	0.00 b	0.75 c	0.50 b	0.25 b	0.00 c	0.50 c	0.5 c	1.0 d
Weedy	11.75 ab	31.25 a	88.25 a	91.25 a	92.50 a	93.75 a	95.00 a	95 a	95 a
P-value	0.0234	0.0024	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

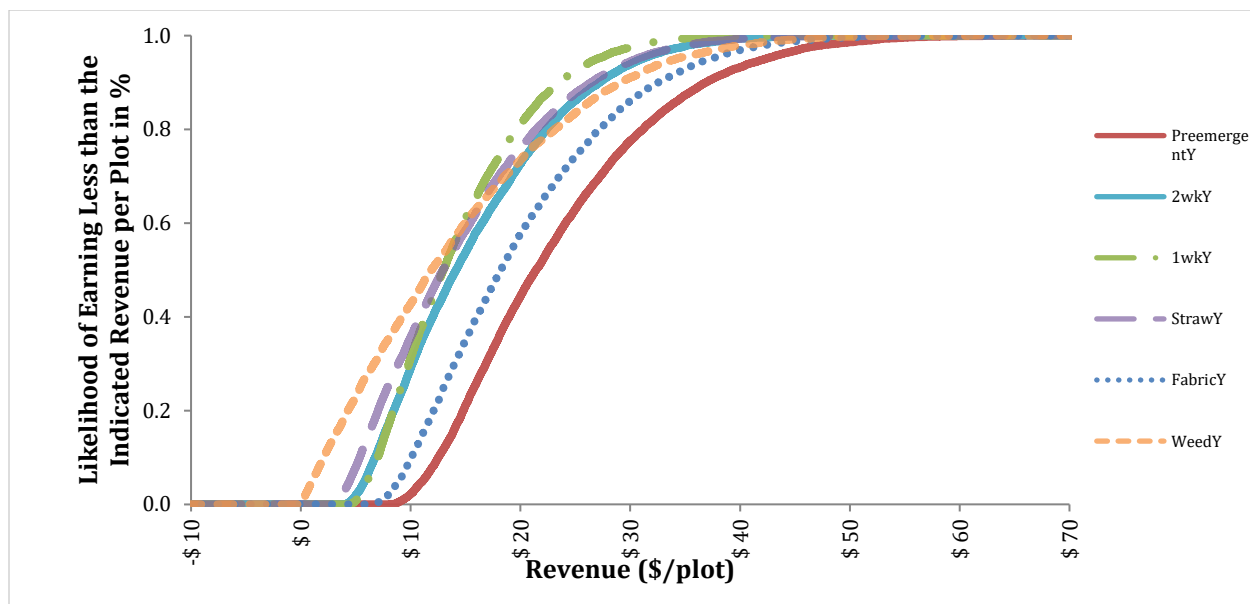
Notes: 1 wk Hand refers to weekly hand-weeded treatments. 2 wk Hand refers to bi-weekly hand-weeded treatments.

Figure 1. Partial Profitability per Plot by Weed Control Method.



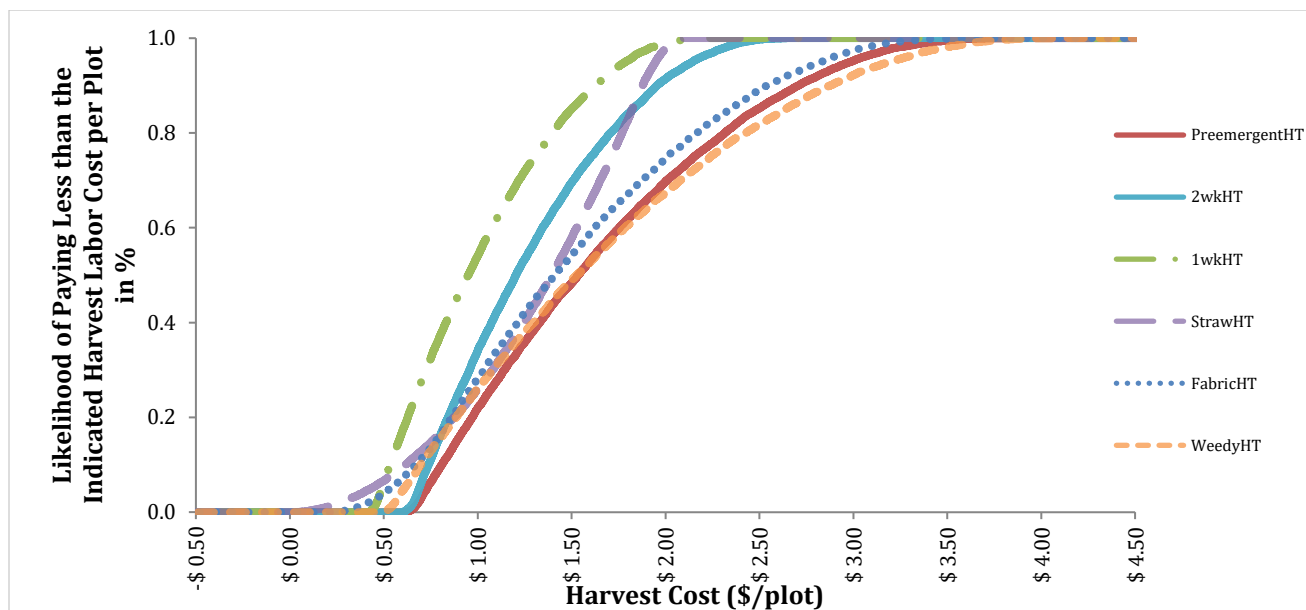
Notes: Partial profit was yield * price – labor cost – materials costs. Yield, market price, wage rate, time estimated to perform planting, weeding and harvest were all based on fitted triangular probability density function with simulated partial returns as results of 10,000 randomly selected observations from each of the probability density functions put into the program.

Figure 2. Revenue per Plot by Weed Control Method



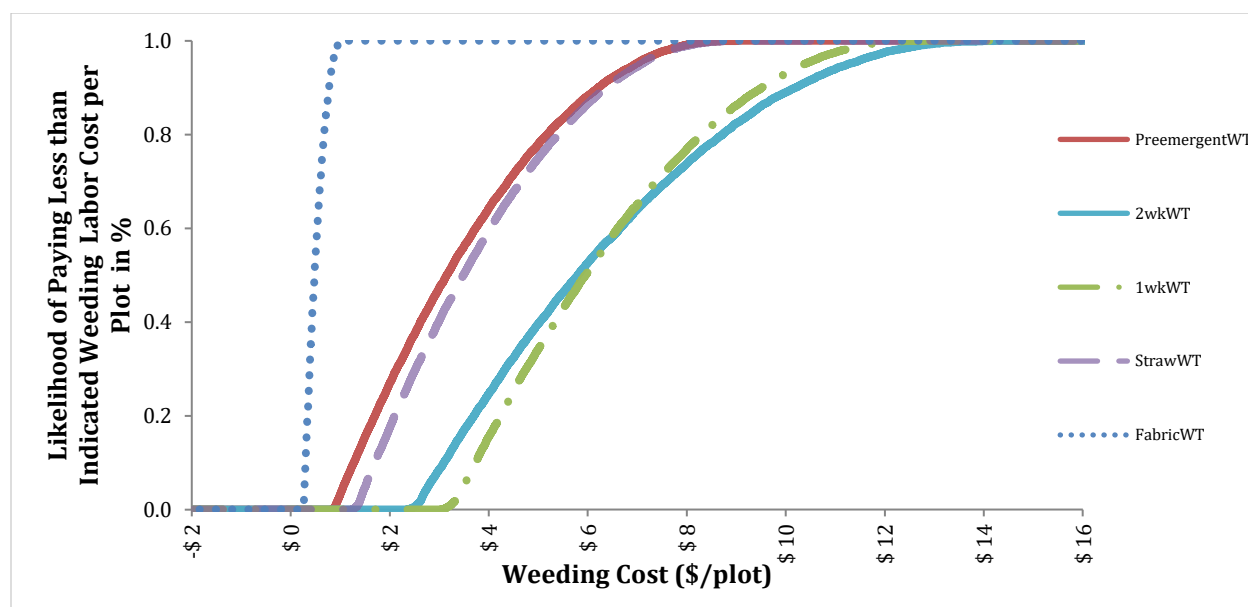
Notes: Y=Yield. Revenue was calculated by multiplying the yield distribution in (kg/plot) by the market price distribution.

Figure 3. Harvest Labor per Plot by Weed Control Method.



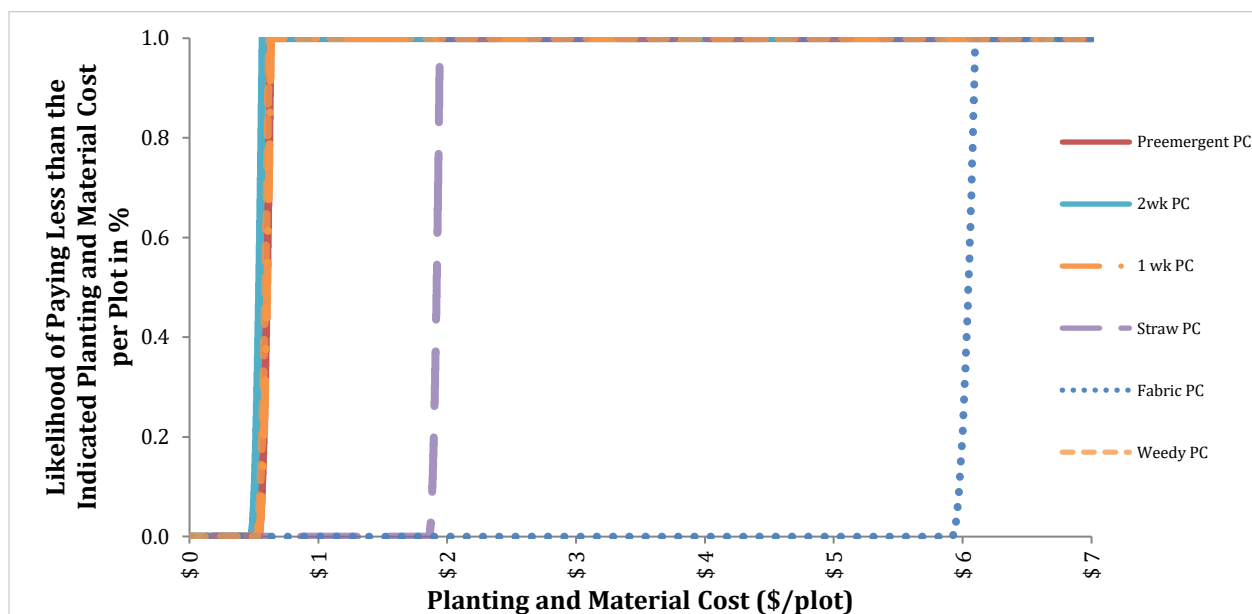
Notes: HT=Harvest time. Harvest labor was calculated by multiplying the time distribution estimated from cumulative time it took to harvest fruit over the 4 timed harvests by the distribution of wage rates shown in Appendix Table 1.

Figure 4. Weeding Labor Cost per Plot by Weed Control Method.



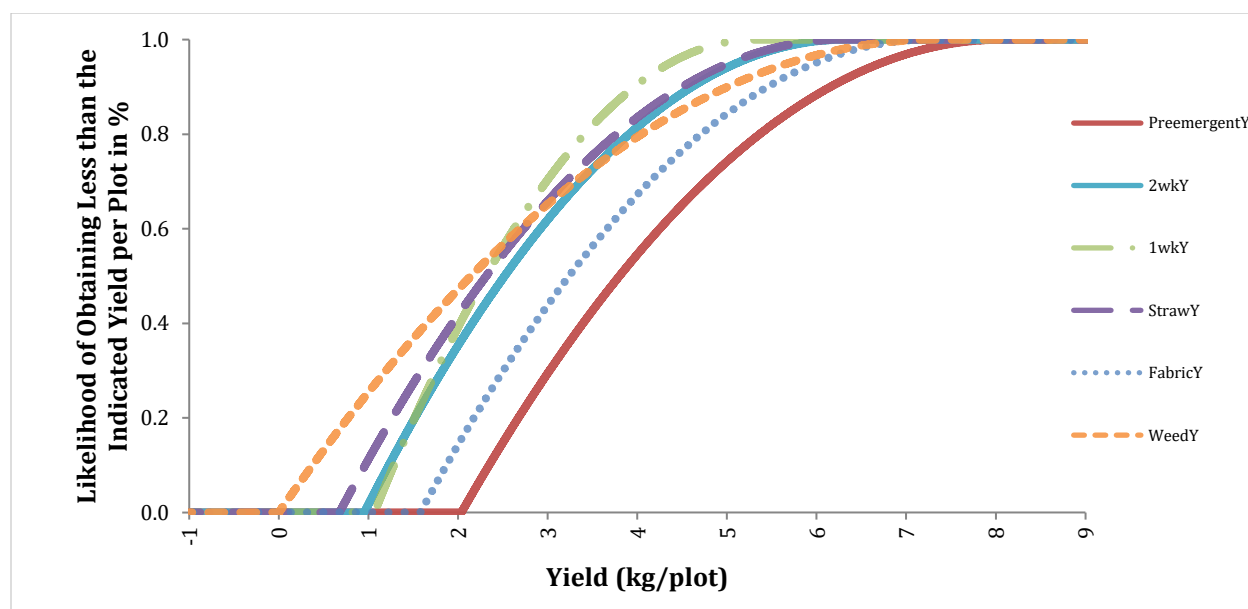
Notes: WT= Weeding Time. Weeding labor cost was calculated by multiplying the weeding cost distribution estimated from cumulative cost it took to weed plots over the weeks in the high tunnel by the distribution of wage rates shown in Appendix Table 1.

Figure 5. Planting and Material Cost per Plot by Weed Control Method.



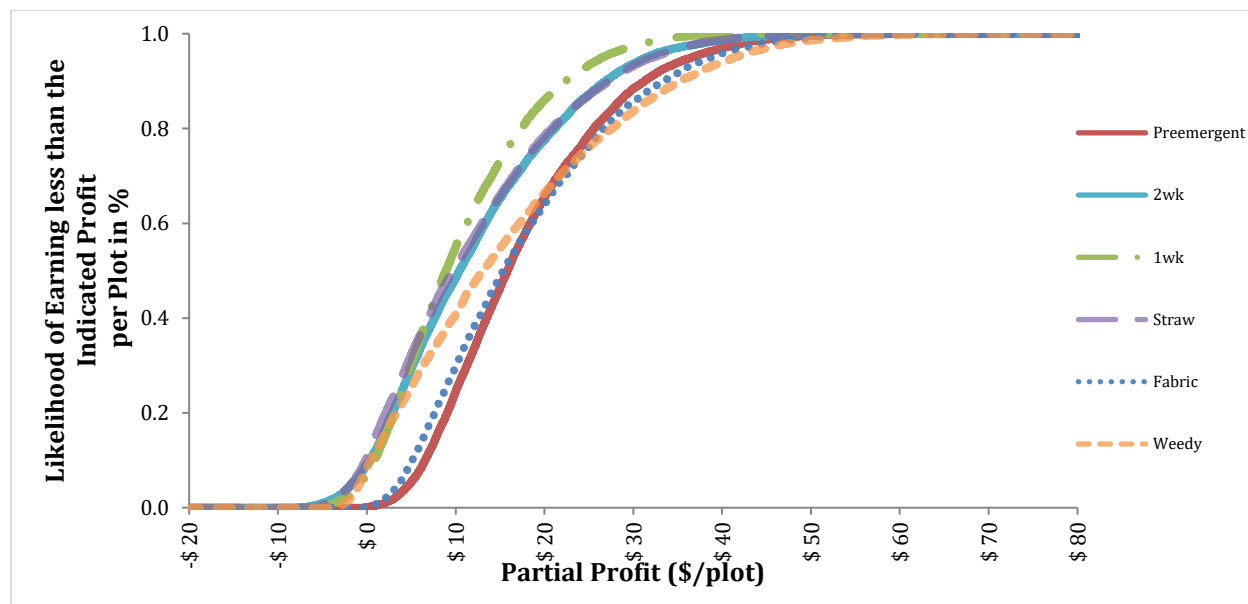
Notes: PC=Planting cost. Planting cost was calculated from the time it took to plant multiplied by labor cost. Material cost was calculated from the price of implementation of treatments. Dual Magnum preemergent herbicide was bought in a 9.45 Liter jug at \$26.83 per liter and costing \$44.82 per hectare, applied to 2.78 m² plots at 1.68 kg/hectare. Straw mulch was bought in bales weighing 18.14 kgs and was applied at approximately 4 kgs per plot, costing \$6.25/plot. Landscape fabric was \$89.99 for a 1.22 m by 9.44 m roll applied to a 2.78 m² plot at \$2.25 per plot. Staples were included in the landscape fabric curve total, at \$44.98 for 500 staples, and approximately 30 staples used per plot, coming out to \$2.69 per plot. This brought the landscape fabric material cost total to \$4.94 per plot.

Figure 6. Yield per Plot by Weed Control Method.



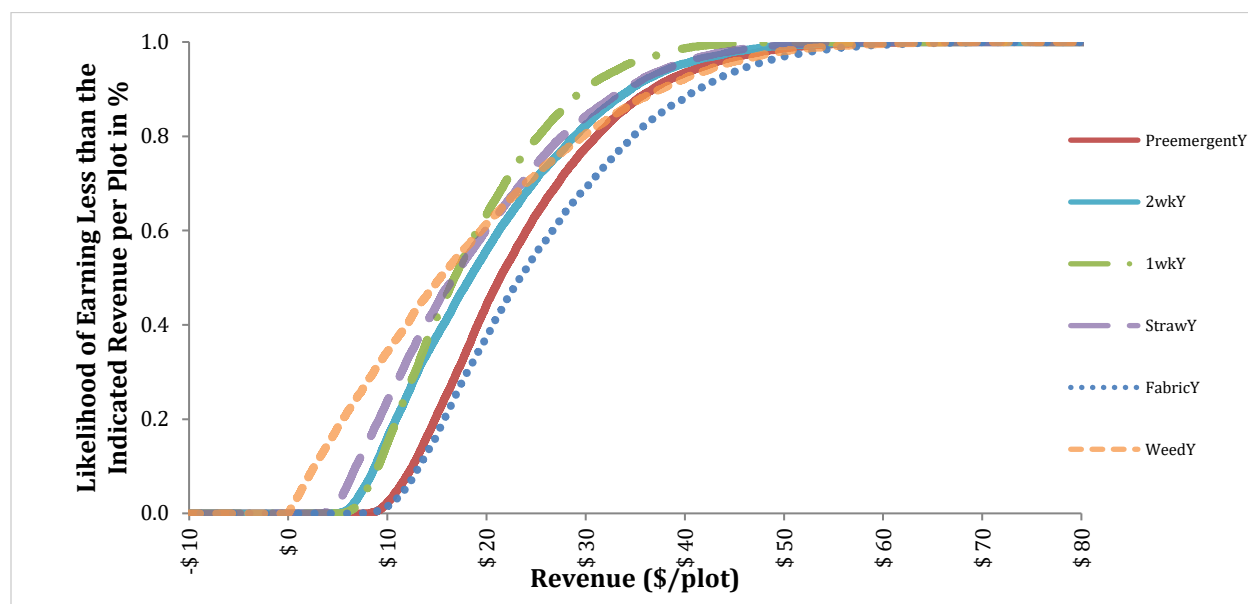
Notes: Y=Yield. Yield was calculated by cumulative marketable fruit weight in kg per plot from 4 harvests. Cull tomatoes were not included in the yield distribution, because they were unmarketable.

Figure 7. Modified Profit with 40 cent/kg Organic Premium by Weed Control Method



Notes: The 40 cent/kg premium came from the amount the revenue for fabric treated tomatoes had to increase to match the partial profit of preemergent herbicide near the 50th percentile.

Figure 8. Modified Revenue with 40 cent/kg Organic Premium per Plot by Weed Control Method



Notes: Y=Yield. This figure represents the amount that revenue of the organic plots would increase if tomatoes were sold at a 40 cent/kg premium.

Appendix

Appendix Table 1. Parameter estimates and descriptive statistics for probability density functions for planting material and labor cost, weeding and harvest labor per season, tomato yield, hourly wage rate, tomato market price and organic premium across different weed control methods as sampled from triangular probability density functions fitted from experimental data using Monte Carlo simulation with 10,000 iterations with @Risk software.

Name ^a	Min.	Mean	Max.	Percentiles	
				5%	95%
Planting Material & Labor (\$/plot)					
Weedy Control	\$0.52	\$0.58	\$0.62	\$0.54	\$0.61
Preemergent	\$0.53	\$0.60	\$0.63	\$0.55	\$0.63
2 wk	\$0.48	\$0.54	\$0.57	\$0.50	\$0.56
1 wk	\$0.53	\$0.60	\$0.63	\$0.55	\$0.63
Fabric	\$5.92	\$6.04	\$6.10	\$5.96	\$6.09
Straw	\$1.86	\$1.91	\$1.94	\$1.88	\$1.94

Weeding Labor (sec./plot)					
Preemergent	47	186	463	58	371
2 wk	135	336	731	150	602
1 wk	176	339	661	188	555
Fabric	14	27	54	15	45
Straw	71	203	465	81	379
Harvest Labor (sec./plot)					
Weedy Control	35	112	264	41	214
Preemergent	44	111	244	49	200
2 wk	43	86	171	46	143
1 wk	30	68	144	33	119
Fabric	14	102	231	36	189
Straw	0	88	133	29	130
Yield (kg./plot)					
Weedy Control	0.00	2.44	7.29	0.19	5.68
Preemergent	2.04	4.04	8.05	2.19	6.71
2 wk	0.95	2.73	6.29	1.09	5.10
1 wk	1.07	2.48	5.29	1.17	4.36
Fabric	1.58	3.47	7.22	1.72	5.98
Straw	0.68	2.54	6.21	0.82	5.01
Wage Rate (\$/hr)	11.92	13.40	14.15	12.41	14.10
Market Price	0.92	1.44	2.25	1.04	1.99
Organic Premium	0.003	0.40	0.81	0.12	0.68

Notes: ^a Planting material and labor charges became stochastic by multiplying the average observed time required to prepare a plot across four replicates with the wage rate distribution and adding materials costs of \$0.01/plot for preemergent valued at \$26.83 per liter or \$18.14/acre, \$1.41/plot for straw at a straw bale price of \$6.25 per 18.14 kg/bale, 4.08 kg/plot and \$2.25/plot for fabric and \$2.70/plot for staples (\$89.99 per 1.2192 m x 91.44 roll of fabric and \$44.98 for 500 staples). Weeding labor was fitted using 20 observations across 5 bi-weekly weeding events across the four replicates (for hand weeded plots weeded weekly (1 wk), weekly observations were aggregated to bi-weekly totals prior to fitting the distribution) except for the weedy control. Harvest labor and yield were fitted using 4 weekly harvest events across 4 replicates or 16 observations per strategy in total. Market price minimum, mode and maximum were set to \$0.92/kg, \$1.44/kg, and \$2.25/kg. for fresh market tomatoes similar to values reported by USDA (add reference). The organic premium had a modal value of \$0.43/kg with a minimum of \$0.00/kg and a maximum twice the mode when solved for the breakeven premium needed to have partial returns equal between preemergent herbicide and fabric weed control management strategies.

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