Productivity, Economics, and Fruit and Soil Quality of Weed Management Systems in Commercial Organic Orchards in Washington State, USA

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Abstract

Organic tree fruit producers often rely on tillage in the tree row to control weeds and disrupt rodent pest habitat. This inexpensive practice can potentially damage the trees' trunk and roots, thereby reducing yield and fruit quality. In contrast, mulching under the trees to suppress weeds often improves tree performance but at a high initial installation cost, whereas flame weeding and organic-compliant herbicides can control weeds without disturbing the soil. These three systems of weed management in the tree row were compared in commercial, certified organic apple and pear orchards in Washington State, USA, to determine the effectiveness for weed control, and the impacts on tree performance, soil organic matter, and economic return of each system when taking into account both the cost of the weed control itself and its impact on fruit yield and quality. Mulching produced a large net economic benefit relative to tillage, more so in the apple orchard that had sandier soil than in the pear orchard on a loam soil. Flame weeding was similar to tillage in cost, whereas organic herbicides proved extremely expensive and relatively ineffective. Tillage did not lead to a decline in soil organic matter over three seasons, nor did mulching increase it. Overall, mulching led to better tree performance and economic returns but was not a successful stand-alone weed control practice over three years. A combination of flaming and tillage and/or mulch may offer the best overall results.

Keywords apple, pear, tillage, mulch, flame weeding, soil organic matter, economics

Introduction

Organic tree fruit production continues to expand in a number of regions in response to steady increases in consumer demand for organic fruit (Granatstein et al. 2013). Given the limited number of fertilizers and herbicides available for organic production, orchard floor management takes on a more critical role for organic growers. The orchard floor affects nutrients, water, and pests, all of which influence tree performance and orchard economics. Weed control interacts with all of these aspects. Typical organic orchard weed control approaches include tillage in the tree row, which disturbs the root zone soil, and approaches that do not disturb the soil, such as flame weeding, mowing, weed fabric, and mulches (Granatstein et al. 2010), along with periodic mowing of the grass drive alley. Organically-compliant herbicides have been tried with limited success. Tillage for weed control, the most common practice in the Pacific Northwest (D. Granatstein, unpublished data), has been linked to decreased tree growth, lower fruit yield, smaller fruit size, and loss of soil organic matter (Woolridge and Harris 1989; Merwin and Stiles 1994; Neilsen et al. 2003; Granatstein and Sánchez 2009; Granatstein et al. 2010). These first three issues are directly related to orchard profitability, while loss of soil organic matter can affect the requirement for growers to "maintain or improve soil quality" under the National Organic Program (USDA 2001). Monitoring trends in soil organic matter is the most common way of demonstrating compliance with this requirement. In contrast, previous studies on mulching within the tree row have generally led to positive tree responses for growth, yield, and/or fruit size (Zhao et al. 2002; Neilsen et al. 2003; Granatstein and Mullinix 2008; Granatstein et al. 2010), as well as improved soil quality (Forge et al. 2003; Yao et al. 2005). While organic apples and pears in Washington State have consistently garnered a price premium over conventional fruit for over 15 years (Kirby and Granatstein 2012), in some years the premium has been quite small and may not have covered the increased costs of organic production, which are often dominated by weed control in the tree row, the most challenging, important and costly location.

This study was conceived to help determine whether alternative approaches to weed control that do not cause soil disturbance would perform better than a tillage-based system in terms of crop productivity, tree growth, economic return, and fruit and soil quality. The experiment was conducted in two mature, commercial organic orchards (apple and pear) using large-scale replicated plots in order to overcome some of the variability that often occurs with small-plot orchard trials.

Materials and methods

Description of orchards and management practices

The study was conducted in two commercial organic orchards in Washington State, USA. A mature apple (*Malus* x *domestica* Borkh. cv. Gala/M.26) orchard, located near Royal City, WA (latitude 46.92N, longitude 119.84W), was planted in 2004 on a Kennewick fine sandy loam soil (Xeric Torriorthent) and was certified organic starting in 2006. The orchard was on a west-facing slope (10-15%), with trees planted across the slope at 1.22 m between trees x 4.27 m between rows, and trained to a vertical trellis. A mature pear (*Pyrus communis* cv. d'Anjou/OHxF97) orchard, located near Tonasket, WA, (latitude 48.67N, longitude 119.52W), was planted in 1992 on a Nighthawk loam soil (Calcidic Haploxeroll) and was certified organic since 2008. The orchard was generally flat, with trees spaced 5.49 m x 5.49 m apart. Common management practices across plots in both orchards included insect pest management based on codling moth pheromone mating disruption and organic-compliant insecticides, organic compliant-disease control materials, annual fall additions of 6.7 MT ha^{-1} of chicken manure compost (4% total N; C:N ~10:1) to the tree row, mowing drive alleys 3-4 times per year and undertree irrigation (microsprinklers in apple, impact sprinklers in pear) according to tree need. Blossom thinning with lime sulfur was done on apples only. Fruit at both orchards were harvested by hand and placed in bins that were trucked to the fruit storage and packing facility.

The same three treatments were used in the tree rows at both orchards (Table 1): 1) tillage (Wonder Weeder, Harris Mfg., Burbank, WA), five passes per year, as the standard control. 2) organic herbicide [per application mix of WeedPharm™ (Pharm Solutions, Inc., Port Townsend, WA) 20% acetic acid at 112 L/applied ha; citric acid at 17.9 kg/applied ha; horticultural oil at 18.7 L/applied ha, and 60.57 L water] applied four times per year in 2009, and flame weeding (Red Dragon GP-750, Flame Engineering Inc., LaCrosse, KS) used five times per year (herbicide/flaming). The herbicide/flaming plots were treated only with herbicides in 2009, herbicides early in 2010, then flaming for the balance of the 2010 season, and flaming only in 2011 due to no better weed control and much higher cost of the herbicides. 3) wood chip mulch (bark and wood debris from a lumber mill, 10 cm thick, 0.9 m wide) over a weed barrier fabric (non-woven landscape fabric, Geotech South, Macon, GA) plus flaming (mulch/flaming). The mulch/flaming plots were flame-weeded in 2010 and 2011 to attempt to control the weeds that were emerging on top of or through the wood chips. All treatments were first applied during July-August 2009. Each treatment was replicated four times in a randomized complete block design at each site, with each plot consisting of three rows. Plot size was approximately 0.28 ha in apple and 0.36 ha in pear.

In both orchards, hand sampling was done on 10 trees of relatively uniform size in the center row of each plot for tree growth, fruit yield, average fruit size, fruit quality, and tree leaf N. In addition, a commercial harvest from each plot was done yearly (2009, 2010 and 2011), where all fruit from the center row of each plot were hand harvested into bins by a commercial picking crew. Each plot had a unique bin tag number for those bins harvested from the plot to enable tracking through the fruit packing process. Bins were taken to the fruit warehouse for cold storage. When the fruit were designated for sale, bins from each plot were run as a group on a commercial packing line, with all plots from an orchard run on the same day. Data were recorded by plot for fruit size distribution, grade, and sales price to allow for statistical analysis. Actual pear yields per hectare for 2009 could not be calculated as the number of trees included in the harvest differed among plots due to selective harvest based on maturity, and this number was not recorded. The irrigation system in the apple orchard was upgraded after the 2009 harvest in order to provide water more frequently during the hottest part of the growing season, and this raised fruit yields throughout the entire orchard, based on historical records.

Field sampling and measurements

Tree growth was measured as cross-sectional area of the trunk at 20 cm above the graft union (TCSA) on apple, and at the base of large limbs on pear trees, calculated as limb cross-sectional area (LCSA). Results are reported as percent increase over two years to normalize for differences in tree size at the start of the trial. Measurements were taken in July and October 2009, October 2010, and October 2011. Fully expanded tree leaves on new terminal shoots, 30 leaves per plot, were sampled in late July 2010 and 2011. Leaves were washed in distilled water, dried, ground, and analyzed for total N by combustion (SoilTest Farm Consultants Inc., Moses Lake, WA). Apple fruit were harvested, counted, and weighed per sample tree, while pear fruit were collected and measured per sample limb. A sample of 30 undamaged fruit of similar size (~215 g for apple, ~260 g pear) were randomly collected from the harvested fruit for each plot, packed in boxes, and stored at 2.2^{o}C until they were analyzed for fruit quality. Weed biomass was collected in mid-summer prior to a weed control event from three random locations per plot in the tree row with a 0.25 m^2 hoop, clipping the weeds at ground level, drying them, and determining dry matter. Weed cover was measured in the tree row with a point-intersect method on four or five dates from early May to early September. Three subsamples per plot were taken, noting points either as broadleaf weeds, grass weeds, or bare ground. Soil samples (five composite cores per plot from the tree row) were taken in July 2009 prior to treatment application for baseline total C, Particulate Organic Matter (POM), and mineral nutrients; in October 2010 for POM; and in October 2011 for POM, total C, and nutrients. POM samples were collected separately from 0-5 cm and 5-10 cm depths to monitor potential short-term changes in soil carbon relative to the longer-term change anticipated for total C. The total C and nutrient samples (0-30 cm depth) were analyzed with standard methods (combustion for total C and N; SoilTest Farm Consultants, Moses Lake, WA). POM C and N were determined with the method of Cambardella and Elliott (1992). Vole damage was assessed in March of 2010 and 2011, visually rating trunks of 20 trees per plot on a scale of 0 (no damage) to 3 (total girdling).

Fruit quality analysis

Apple fruit quality was measured just after harvest, while pear fruit quality was measured after eight weeks in refrigerated storage to approximate physiological maturity. No pear fruit quality measurements were taken in 2010 because of fruit deterioration during storage. Twenty similar sized fruit per plot were measured for weight, firmness, soluble solids concentration, and starch index (apple only). A pooled sample of fruit skin (peel) and flesh (cortex) from each plot was measured for total phenolics concentration. Fruit firmness after skin removal was measured on an automated Güss Fruit Texture Analyzer (Model GS-20, software version 5.0, Güss Manufacturing Ltd., Strand, South Africa). Soluble solids concentration was measured with a digital refractometer (Atago Model PR-101 Palette Refractometer, Atago Co., Ltd., Tokyo, Japan) for juice expressed from fruit cortical tissue taken just under the skin. Two measurements each of firmness and soluble solids were made at the equator on opposite sides of each fruit. The starch-iodine index for individual apple fruit was evaluated using the method of Blanpied and Silsby (1992). Each fruit was cut in half across the equator, sprayed with a potassium iodide solution, incubated for 5 min, and then its pattern of staining was compared to the Cornell starch-iodine index chart (8-point scale) for apples.

As certain consumers are interested in foods with elevated levels of anti-oxidants, the effect of the treatments on total phenolics (an indicator of anti-oxidant content) was evaluated. Total phenolic (TP) compounds were measured with the Folin-Ciocalteu phenol (F-C) reagent with modifications (Singleton et al. 1999). An extract from powdered, frozen fruit tissue (200 mg peel or 500 mg flesh) was combined with either saturated Na_2CO_3 or water and the absorbance of each was measured at 760 nm in a UV-visible spectrophotometer (Model HP8453, Hewlett-Packard Co., Palo Alto, CA). The concentration of phenolic compounds was determined by subtracting the absorbance of samples containing Na_2CO_3 from those containing water, and quantified as gallic acid (3,4,5-trihydroxybenzoic acid) equivalents based on standard curves.

Financial analysis

All costs of each weed control treatment were recorded by the grower and were the same at both orchards. Costs for the other operations common to all treatments (e.g. pruning, thinning, fertilization, pest management, irrigation) were the same across treatments within an orchard. A partial budget was developed for each weed control system to determine cost/ha/yr (Online Resource 1). Revenue per plot was determined from the commercial pack-out, using actual sales prices. Harvest cost was calculated for each plot by multiplying the per bin picking payment for that year by the number of bins picked. Finally, grower return after harvest and weed control cost was calculated for each year, then summed for the three-year period. Tillage was then set to zero, being the control treatment for comparison, and the relative return compared to tillage was calculated for the other treatments.

Statistical analysis

Data were analyzed using Statistix 9 (Analytical Software Inc., Tallahassee, FL). All data were tested for normality prior to analysis. Only tree growth data were not normally distributed and were ln transformed. Data were analyzed using ANOVA for single year data and repeated measures ANOVA for multi-year data, and FLSD for mean separation with significance at p=0.05 unless otherwise noted.

Results and discussion

Weed control

Quackgrass (*Elymus repens* (L.) Gould) was the dominant weed each year in the apple orchard and widely infested the tree rows. It was also present in the pear orchard, but the site was more dominated by broadleaf weeds (data not shown). In 2010, the first full season with treatments in place, mulch/flaming reduced weed biomass to near zero in apples, while weed biomass between tillage or herbicide/flaming was not significantly different (Fig. 1). The weed fabric under the mulch in apples did minimize the infestation of the mulch layer by quackgrass rhizomes in 2010, but this effect was greatly diminished in 2011 (data not shown). In 2011, weed biomass with mulch/flaming did rise, while weed biomass for the other two treatments showed a significant decrease. Approximate changes in weed percent cover from 2010 to 2011 were as follows: tillage, 72% to 47% *; herbicide/flaming, 84% to 67% ns; mulch/flaming, 20% to 45% * (* p=0.003, SEM= 5.57%). Weed biomass in pears was also near zero for mulch/flaming plots in 2010, with a significant difference from herbicide/flaming plots only (Figure 1). By 2011, weed biomass was similar in all pear treatments, with overall levels similar to the herbicide/flaming plots in the previous year. Weed biomass increased significantly in the mulch/flaming plots. Weed percent cover in pears did not change significantly between years (50% in 2010, 41% in 2011; p=0.27, SEM=5.81) or among treatments (Tillage 44%, herbicide/flaming 48%, mulch/flaming 45%; p=0.80, SEM= 4.66).

One unanticipated effect of the wood chip mulch with fabric underneath was attraction of meadow voles (*Microtus pennsylvanicus*) to these plots in the apple orchard where they entered under the fabric and moved to the tree trunks, to which they caused extensive partial girdling. Trees in mulch/flaming plots had significantly more damage (1.45 on 0-3 scale; p=0.04; SEM=0.48) than either tillage (0.15) or herbicide/flaming (0.05). Previous studies of wood chip mulch without fabric found vole presence no different than bare ground or tillage (Wiman et al. 2009). In another orchard with the same management comparisons as this study, heavy quackgrass infestation, extensive vole damage to trunks of young trees, and the same pattern of weed suppression were seen (data not shown).

Clearly, mulching along with supplemental flaming did not provide superior weed control for more than a year when perennial weeds like quackgrass were present. In a previous study at a site where quackgrass was not present, a wood chip mulch without fabric provided acceptable weed control for three years (Granatstein and Mullinix 2008). Organic herbicide, used in 2009, did not provide any better weed control than flaming, used in 2010 and 2011, with the latter having a much lower cost (see below). Currently available organic compliant herbicides appear insufficient to control invasive perennial weeds, such as quackgrass.

Tree growth

Mulch/flaming in apple increased tree growth over the other treatments, as measured by percent increase in trunk cross-sectional area (Table 2). This level of growth is typical of apple orchards of this age (i.e. 5-10 years). There were no treatment effects on tree growth for the older pear trees. In an Australian study of mature pears with either cultivation, white clover, bare ground, or straw mulch in the tree rows, the straw mulched trees had a 40% increase in root length compared to the bare ground treatment, while cultivation led to a 42% decline in root growth; however, above-ground, tree growth was not measured (Cockroft and Wallbrink 1966). Impacts on roots were not measured in the current study but were hypothesized to express themselves through differences in tree growth, especially from the root pruning effects of tillage. However, this was not observed at either site.

Tree leaf N (%) showed a significant decline ($p<0.002$) at both sites from 2010 to 2011 (Table 2), with no differences among treatments and no treatment by year interaction. Variability was low, with a Coefficient of Variability of 4% for apple and 3% for pear. All treatments were at levels not associated with N deficiency (Stiles and Reid 1991). The weed control management systems employed had no consistent impact on either tree growth or leaf N over the duration of this study.

Fruit yield, size and quality

Commercial harvests by plot were done for three years in apples. There were no treatment by year interactions. Yields in 2009 were significantly less ($p=0.0001$) than in 2010 and 2011. When analyzed with repeated measures, there were no significant treatment effects on yield. When each year was analyzed separately, mulch/flaming yields were higher than in the other treatments at $p=0.06$, 0.08, and 0.01, for 2009, 2010 and 2011, respectively (Table 3), and 3-year cumulative yields for mulch/flaming were significantly greater than the other treatments. For pears, there were no significant treatment, year, or interaction effects using repeated measures analysis. When analyzed by year, fruit yield for mulch/flaming was significantly higher ($p=0.04$) in 2011 than the other treatments. There were no treatment differences for cumulative yield

(Table 3). A regression of weed biomass versus fruit yield showed no relationship for pears, and a weak inverse relationship for apples (p=0.009; r^2=0.51). Results support the hypothesis that mulch/flaming can increase fruit yield over an undisturbed weed-suppressed tree row (herbicide/flaming in this study), especially on a more coarse-textured soil. They do not show that tillage lowered yields (presumably from root pruning or other tree damage) compared to the undisturbed herbicide/flaming plots in this study.

No clear trend emerged for treatment effects on fruit size (data not shown). In apples, there was no treatment effect in 2009 or 2011, but mulch/flaming led to significantly greater (p=0.04) percentage of fruit in the economically optimal sizes of 202-227 g and 228-249 g, increasing the number of these sized fruit by 40% over the other treatments. There were no significant treatment effects on fruit size in pears. There were no significant treatment effects on fruit quality parameters for firmness, soluble solids, starch index, or flesh phenolics in any year (data not shown). The only statistically significant treatment effect for fruit quality was on skin phenolics for pears in 2011, where tillage resulted in more phenolics than herbicide/flaming.

While previous studies have shown effects of both tillage and mulch on tree growth, yields, and fruit size, none have looked comprehensively at fruit quality. An improvement in fruit quality, including the antioxidant phenolics content, would provide another potential economic benefit from a given management system. Since no differences were found other than the pear skin phenolics in one year, the results suggest that none of these weed control management systems negatively impacted fruit quality.

Soil quality

In this study, soil organic matter (SOM) was considered the key parameter to monitor for changes in soil quality. Organic compliance requires “maintaining or improving soil quality” (USDA 2001) and this can be met by maintaining or improving soil organic matter. Mulching adds large quantities of carbon to the soil, but it remains primarily on the surface. Tillage is known to lead to decreases in SOM due to enhanced oxidation (Merwin 2003), but can also aid decomposition of green plant material, such as weeds, and incorporate organic amendments like compost. Thus, while tillage is commonly used for weed control and is generally less expensive than other management options, if it jeopardizes organic certification and access to price premiums, it may not be economically desirable for an orchard enterprise. Typical compost application rates, as used in these orchards, do not always maintain SOM in sandier soils in this semi-arid environment.

Overall, there were no significant treatment effects or changes over time for soil C, both total C and Particulate Organic Matter C (POM-C) using repeated measures analysis (data not shown). Despite the large addition of organic C with the wood chip mulch, no change in soil C was detected, likely due to inhibited mixing of the mulch into the soil by organisms because of the underlain weed fabric. In addition, the sampling protocol excluded organic residues on the soil surface from the sample, used a 30-cm depth, which would have diluted any changes that occurred near the surface, and did not adjust for any differences in soil bulk density. The POM-C tests were intended to look more closely at the surface layers and at a carbon fraction that often responds more quickly than total C (Cambardella and Elliott 1992; Marriott and Wander 2006). In a long-term study in New York State, a 15-cm thick bark mulch application raised the soil organic matter by 18% one year after application, and by 72% after fourteen years with a total of six applications (Atucha et al. 2011). None of the weed management systems in this study altered soil organic matter in the tree row, and thus the concern that using tillage for weed control might jeopardize soil quality was unsubstantiated.

Financial performance

Fruit from each plot were picked, graded, packed and priced separately so that actual revenues for each treatment could be analyzed. The annual costs for each weed management system (Table 4) were also recorded each year by the grower and are explained below. Because the plots were otherwise treated identically within an orchard, the costs differed only in weed management and harvest costs.

Tillage Costs

Tillage was used as the baseline weed management system as it is currently most commonly used by Washington state organic growers (Pitts et al., 2010). The cost of tillage was modest, about $US262 per hectare ($US106 per acre) per year for five passes through the orchard with the tractor-mounted WonderWeeder (Online Resource 1a). One third of this cost is associated with the required incremental equipment costs, specifically the WonderWeeder and front three-point lift required on the tractor. The other two thirds of the costs are from the direct operating costs, including fuel, labor, and the cost of the tractor.

Mulch Costs

Mulch was a one-time expense that cost $US2,969 per hectare ($US1,202 per acre), nearly ten times the annual cost of tillage (Online resource 1b). In previous trials, mulch has provided satisfactory weed control for 2-4 years, and likely provides growth benefits beyond that for the trees. Mulch application was 10 cm (4 inches) thick and 0.9 m (3 feet) wide along the tree row. The mulch material itself represented three quarters of the cost. In this study, the material was obtained from a source at no charge but had to be transported 97 km (60 miles) by truck. If material had been in closer proximity to the orchards, this cost would have been less. One quarter of the cost was incurred from the application of such a large amount of bulk material using a rented mulch spreader (Whatcom Mfg., Lynden, WA, USA).

Organic Herbicide Costs

The costs for applying organic compliant herbicides were $US1,256 per hectare ($US509 per acre) when the rate and concentration were raised to levels that provided some degree of weed control (Online resource 1c). Initially, lower rates of WeedPharm (20% acetic acid), citric acid, and oil were used, but they were not effective and the treatment was changed to the maximum allowable rate. A low-volume Enviromist weed sprayer (Enviromist Industries Pty. Ltd., Berri, South Australia) was purchased to see if that could reduce costs by applying lower volumes of material. High concentrations at low volumes were more effective than low concentrations at high volumes, however results were still insufficient to provide any meaningful control. Additionally, the acidic solution quickly destroyed the Enviromist sprayer. Consequently, the only way to achieve any visually obvious control was through the use of large quantities of spray material. Other organic compliant herbicide materials were tested in adjacent blocks as well, including GreenMatch (Marrone Bio Innovations, Davis, CA, USA) and Burnout Organic Herbicide (St. Gabriel Organics, Orange, VA, USA). GreenMatch at higher rates was more effective (data not shown) but it was more costly than the WeedPharm/citric/oil solution. Regardless of herbicide product, weed control with these organic compliant herbicides was expensive and marginally effective.

Flame Weeding Costs

Weed control expense with flaming, using five passes per year, was $276 per hectare ($112 per acre), similar in cost to tillage (Online resource 1d). Results were generally better than what was achieved with the organic herbicides, and therefore, for most of the second year (2010) and all of the third year (2011) flaming was solely used for the herbicide/flaming treatment. However, for the economic comparisons below, organic herbicides were included as an expense only for 2009, with flaming as an expense for 2010 and 2011. Flaming was also employed on the mulch treatment in 2010 and 2011 because weeds began to grow through the mulch in 2010, and that is reflected in the weed control costs below (Tables 5 and 6). The propane fuel used in the flamer accounted for 45% of the cost of this weed control system. Flame weeding allows for travel through the orchard at higher speeds than when tilling or spraying herbicides.

Apple Orchard Economics

For the apple orchard, fruit production rose substantially from 2009 to 2010 due to overall improved water management in the orchard, and then declined some in 2011 (Table 3). The fruit price per metric ton was not statistically different among treatments in any year. Gross revenue per hectare was statistically higher ($p<0.05$) for the mulch-treated plots in 2011 but not in other years (Table 5). When weed control and picking costs were subtracted from gross revenue, and that value summed over the three years, the mulch/flaming treatment returned $11,798 more than the tillage treatment, while the herbicide/flaming treatment returned $2,338 less. Thus, despite the high initial cost for mulch ($2,969/ha), that treatment returned nearly three times the investment for the mulch.

Few actions in the orchard result in an economic benefit of this magnitude. The economic benefit of the mulch may be underestimated because its tree performance benefits are likely to last beyond the third year (the grower has observed better growth in the mulch/flaming trees for an additional two years already). Additional weed control would be necessary, for example, with a continuation of flaming.

Pear Orchard Economics

For the pear orchard, fruit were harvested separately by plot and graded and packed separately in all three years. However, in 2009, plots were not uniformly picked due to uneven fruit maturity and the number of trees from which the segregated harvest came were not recorded; therefore, yields per hectare could not be calculated and were estimated at 40 MT/ha, based on actual yields from another part of the same orchard block. The chances of a treatment effect in 2009 were deemed unlikely since treatments were applied in late summer of that year, and since there were no yield differences in 2010 A uniform fruit price of $US700 per metric ton was used in the revenue calculations for 2009 (Table 6), based on the actual values from the pack-out reports. There was not a significant difference among treatments in fruit price per metric ton or in gross revenue per hectare for 2010 or 2011. Fruit prices declined for the 2011 crop due to overall smaller fruit size. Revenue differences among pear treatments (Table 6) were smaller than for the apples, likely due to the better quality soil at the site and the older, more uniform stand of pear trees. When weed control and picking costs were subtracted from gross revenue, and that value summed over the three years, the mulch/flaming treatment returned $3,536 more than the tillage treatment, while the herbicide/flaming treatment returned $2,778 less. Again, despite the high initial cost for mulch, that treatment returned 120% of the mulch investment (after paying for the mulch).

The cost of the flaming system alone was similar to tillage, showing it to be a viable weed management strategy that avoids the downsides of potential soil degradation and root disruption from tillage, although these problems were not seen in this study of mature orchards. A hybrid of the two could be used, where tillage is employed at the end of the season to disrupt rodent habitat, while flaming is used during the growing season through harvest. Organic herbicides were much more expensive than flaming and would not be economical.

Conclusions

The basis for this study was the concern that tillage damages the trees' feeder roots that are responsible for water and nutrient uptake, and depletes organic matter, which reduces the water- and nutrient-holding capacity of the soil. The alternative systems used in this study were chosen to eliminate soil disturbance. Research conducted in past decades demonstrated that the herbicide strip-grass alley system plus conventional herbicides and fertilizers was the lowest cost and highest profit approach, despite the fact that in numerous published studies (Zhao et al.

2002; Neilsen et al. 2003; Granatstein and Mullinix 2008; Granatstein et al. 2010) mulching the tree row led to superior tree performance. However, other studies did not examine the economics of the systems and thus could not confirm that the improved performance of using mulch in the tree row led to an economic benefit. The constraints of organic farming systems, with more expensive fertilizers and less effective herbicides, may change the profit equation and challenge conventional wisdom, and this question informed the study design.

Based on the results from this orchard-scale study, mulching along with supplemental flaming did lead to improved tree performance and financial returns on a site with sandy loam soil (apples) more so than on the loamy soil site (pears). Tillage did not lead to an obvious deterioration in tree performance or soil quality, and was similar to the undisturbed system using organic herbicides and flaming. Tillage and flaming offer different advantages for weed control and orchard performance. Tillage provides the benefit of disrupting rodent habitat. Flaming provides the benefit of not disturbing soil and tree roots. A combination of techniques should be considered to maximize benefits, as was attempted with mulching plus flaming. The limited years of weed control that mulches provide may not justify their expense alone, but the tree performance benefits in this study showed mulch/flaming to be an economically beneficial investment. Examining ways to lower the cost of mulch, perhaps by using a thinner layer and/or generating the material within the orchard, would make it even more economically attractive.

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Tables

Table 1. In-row weed control treatments applied over three years (2009-2011).

Treatment	2009	2010	2011
Tillage	Tilled 5 times in tree row	Tilled 5 times in tree row	Tilled 5 times in tree row
Herbicide/ flaming	Herbicides sprayed 4 times in tree row	Herbicides sprayed 1 time in tree row followed by flaming 5 times	Flaming in tree row 5 times
Mulch/ flaming	Fabric mulch with 10 cm wood chip mulch applied over top	No additional mulch; flaming 5 times on top of mulch	No additional mulch: flaming 5 times on top of mulch

Table 2. Two-year cumulative tree growth and tree leaf nitrogen status for three weed control treatments in an organic apple and pear orchard.

Treatment	*Apple*			*Pear*		
	TCSA*	Leaf N (%)		LCSA*	Leaf N (%)	
		2010	2011		2010	2011
Tillage	21.8 b	2.34	2.00	7.8	2.08	1.97
Herbicide/flaming	22.6 b	2.32	1.91	11.3	1.99	1.91
Mulch/flaming	26.9 a	2.39	2.04	10.1	2.00	1.82
SEM	1.22	0.029		5.12	0.022	
P-value	0.05	Trt 0.21, Year <0.001		0.23	Trt 0.08, Year 0.003	

*TCSA = trunk cross sectional area; LCSA = limb cross sectional area; data represent percent increase in size from October 2009 to October 2011. Means with the same letter in the same column are not significantly different. SEM= standard error of the mean. No treatment x year interaction for leaf N. Leaf N 2010 >2011 at both sites.

Table 3. Fruit yields (MT/ha*) from commercial harvest for three in-row weed control treatments in an organic apple and pear orchard.

Treatments	2009	2010	2011	Cumulative Yield
	Apple			
Tillage	15.4	35.3	27.4 b	74.5 b
Herb/flaming	12.3	31.7	29.1 b	73.1 b
Mulch/flaming	17.3	43.0	38.2 a	96.2 a
P-value (annual analysis)	0.06	0.08	0.01	0.05
P-value (repeated measures)	Trt 0.34, year <0.001			
SEM	2.576			5.09
	Pear			
Tillage	-	41.1	43.0 b	91.5
Herb/flaming	-	38.4	44.8 ab	83.2
Mulch/flaming	-	44.7	50.4 a	95.1
P-value (annual analysis)	-	0.18	0.04	0.11
P-value (repeated measures)		Trt 0.47, Year 0.49		
SEM		1.723		3.36

*Based on 420 kg (925 lbs)/bin for apples, 500 kg (1100 lb)/bin for pears. SEM= standard error of the mean. Means with the same letter in column were not significantly different, using annual analysis. No treatment x year interaction for repeated measures analysis. Apple yields in 2009 were significantly less than in 2010 and 2011. Pear yields were not different between years.

Table 4. Costs of different in-row weed controls in commercial organic orchards.

Weed control method	No. Passes/Yr	Cost ($/ha/yr)
Tillage	5	$282.71
Mulch	1*	$2969.43
Herbicide	4	$1256.41
Flaming	5	$280.27

See On-line Resources for detailed costs of each system.
*Mulch was only applied in Year 1.

Table 5. Economic analysis of weed control system in organic apples (yields from Table 3).

Treatment/ Year	Fruit Yield	Fruit Price	Gross Revenue	Picking Cost	Weed Control Cost	Return over Weed Control and Harvest	Return Relative to Tillage
2009	(MT/ha)	($/MT)	($/ha)	($/ha)	($/ha)	($/ha)	($ha)
Till	15.4	540	8,316	787	262	7,267	0
Herb/flame	12.3	549	6,753	629	1,256	4,868	-2,399
Mulch/flame	17.3	554	9,584	885	2,969	5,731	-1,536
2010							
Till	35.3	540	19,062	1,897	262	16,903	0
Herb/flame	31.7	545	17,277	1,704	276	15,297	-1,606
Mulch/flame	43.0	545	23,435	2,311	276	20,848	3,945
2011							
Till	27.4	882	24,167	1,766	262	22,139	0
Herb/flame	29.1	892	25,957	1,876	276	23,806	1,667
Mulch/flame	38.2	897	34,265	2,462	276	31,527	9,388
3-year Total							
Till							0
Herb/flame							-2,338
Mulch/flame							11,798
Picking costs ($/420 kg bin): 2009 – $21.50; 2010 - $22.60; 2011 - $27.10							

Table 6. Economic analysis of weed control system in organic pears (yields from Table 3).

Treatment/ Year	Fruit Yield	Fruit Price	Gross Revenue	Picking Cost	Weed Control Cost	Return over Weed Control and Harvest	Return Relative to Tillage
2009[a]	(MT/ha)	($/MT)	($/ha)	($/ha)	($/ha)	($/ha)	($ha)
Till	40	700	28,000	1,368	262	26,370	0
Herb/flame	40	700	28,000	1,368	1,256	25,376	-994
Mulch/flame	40	700	28,000	1,368	2,969	23,663	-2707
2010							
Till	41.1	714	29,345	1,463	262	27,620	0
Herb/flame	38.4	726	27,878	1,367	276	26,235	-1,385
Mulch/flame	44.7	740	33,078	1,591	276	31,211	3,590
2011							
Till	43.0	520	22,360	1,591	262	20,507	0
Herb/flame	44.8	492	22,042	1,658	276	20,108	-399
Mulch/flame	50.4	502	25,301	1,865	276	23,160	2,653
3-year Total							
Till							0
Herb/flame							-2,778
Mulch/flame							3,536

Picking costs ($/500 kg bin): 2009 – $17.10; 2010 - $17.80; 2011 - $18.50.
[a]Fruit price estimated from packout reports, based on similar grades and sizes among treatments. Gross revenue equals fruit price times the estimated 40 MT/ha yield.

Figures

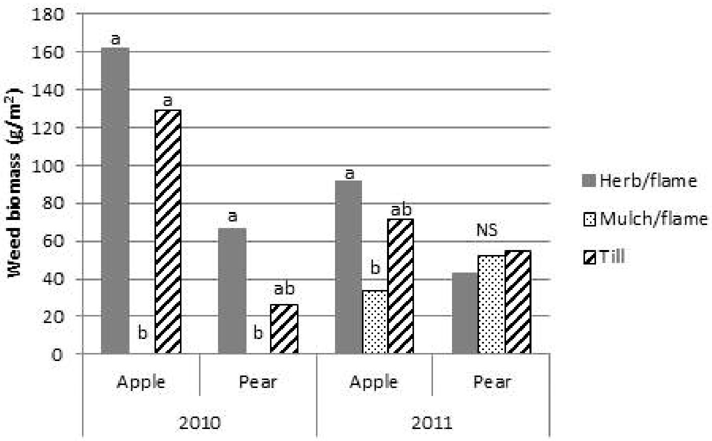

Figure 1. Weed biomass (dry matter) in the tree row of three weed control management systems (herbicide/flaming, mulch/flaming, and tillage). Columns with the same letter are not significantly different (p<0.05) for that orchard.