

American Elderberry Performance, Yield, and Potential Profitability Are Influenced by Weed Management Method

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Abstract. American elderberry (*Sambucus nigra* subsp. *canadensis*) is a rapidly developing specialty crop, native to eastern and midwestern North America. Crop development over the last three decades has been driven by a renewed interest in the crop’s purported health benefits, including antiviral, antioxidant, anti-inflammatory, and immunoregulatory properties. Weed management in American elderberry is a major challenge, but little information or guidance is currently available to producers. The aim of this study was to conduct a comprehensive evaluation of six weed management strategies, with the goal of elucidating cost effective and practical methods for weed management in American elderberry production. Study objectives included evaluating elderberry plant growth, yields, and fruit quality; assessing weed suppression outcomes; and conducting partial budget analyses between management methods. Research plantings incorporating three cultivars (‘Bob Gordon’, ‘Pocahontas’ and ‘Rogersville’) were established in 2022 at two Missouri, USA, sites, and data were collected over the 2023 and 2024 growing seasons. Treatments included woven landscape fabric, woodchip mulch, cover crop [oats (*Avena sativa*) and buckwheat (*Fagopyrum esculentum*)], herbicide (glufosinate and dichlobenil), managed (hand-weeded) control, and unmanaged control. Weed management treatment influenced elderberry plant phenology, fruit quality, plant growth, and cumulative fruit yield. Woodchip mulch and woven fabric treatments resulted in plant heights similar to that of the managed control. Herbicide, woodchip mulch, and woven fabric treatments resulted in the greatest fruit yields, which were similar to the managed control. The cover crop treatment offered yields significantly lower than all treatments aside from the unmanaged control. Compared with the unmanaged control, the woven fabric treatment reduced weed biomass by 44%, while the cover crop, woodchip mulch, and herbicide treatments reduced weed biomass by 71%, 86%, and 91%, respectively. American elderberry cultivar had no influence on weed biomass or population. In the partial budget analysis, herbicide and woodchip mulch treatments performed well at both sites, while the cover crop treatment performed poorly. Profitability of the woven fabric treatment varied between sites. The results indicate that both woodchip mulch and herbicide treatments were effective in reducing weed biomass and improving both plant growth and fruit yield, while also proving to be consistently economically efficient across year, site, and cultivar.

American elderberry (*Sambucus nigra* subsp. *canadensis*), native to much of eastern North America, has recently gained regard as a commercially viable specialty crop (Charlebois et al. 2010). Both fruit and flowers of American elderberry are incorporated into a variety of products including wines, syrups, jams, jellies, and, especially, dietary supplements (Byers et al. 2022). American elderberry products provide health benefits associated with important trace elements, vitamins, and a host of bioactive phytochemicals including flavonoids, anthocyanins, and other polyphenols (Senica et al. 2016; Thomas et al. 2020). However, many technical aspects of American elderberry production remain underdeveloped, requiring basic applied research to mitigate risks assumed by producers (Thomas et al. 2024). The response of American elderberry to common weed management strategies has not been well characterized in current literature. Many producers rely on anecdotal evidence, observations, and literature related to weed management in similar shrubby crops such as blackberries and raspberries (*Rubus* spp.) There is also a lack of information concerning the economic and fruit quality impact of commonly applied weed management methods.

Weeds are one of the most important biotic constraints in agriculture as they compete with crops for sunlight, water, and nutrients (Chauhan 2020). Weeds are also credited with harboring destructive pests and diseases and limiting crop harvestability (Knepp 2022; Warmund et al. 2019; Zimdahl 2018). American elderberry is a rhizomatous shrubby species with multiple stems and a shallow root system. This plant morphology discourages the use of some conventional weed management methods including broad-spectrum herbicides and mechanical tillage (Charlebois et al. 2010; Schmitzer et al. 2012). Currently, producers rely on synthetic groundcovers, organic mulches, and limited labor-intensive mechanical control, often taking an integrated approach by implementing multiple weed management strategies (Savanna Institute 2021).

Research findings in other shrubby specialty crops provide insights into potential impacts of weed management on elderberry plant growth, yields, and fruit quality. Compared with the standard practice of maintaining bare soil in some red raspberry production, synthetic groundcovers have been shown to reduce cumulative weed growth, improve plant growth, and increase fruit yield by 34% (Zhang et al. 2019). Improved plant performance may be the result of an increase in soil temperature and reduction of soil water loss compared with bare ground control. A study featuring micropropagated red raspberry (Trinka and Pritts 1992) compared the effects of weed management treatments including straw mulch, herbicides, synthetic groundcovers, hand-weeded, and unmanaged controls. Reduced weed pressure and increased

soil moisture associated with straw mulch were shown to improve plant performance compared with herbicide and hand-weeded treatments. In hazelnut (*Corylus avellana*) production, applying 10 cm of hazelnut husk mulch was shown to control weeds effectively for 180 d and reduce weed dry biomass by 83% (Mennan and Ngouajio 2012). The use of organic mulches in vineyards has been shown to improve soil characteristics including soil water content and friability (Steenwerth and Guerra 2012). A study from Cavender et al. (2014) found that synthetic groundcovers may result in lower levels of sugars and antioxidants in blackberry fruit when compared with both weed-free and unmanaged controls.

Herbicide application and use of cover crops have not been widely adopted by elderberry producers but may serve as viable weed management options. Herbicide application may be an effective strategy for controlling annual weeds but may shift weed populations to predominately perennial weeds (Elmore et al. 1997). A study by Knepp (2022) found that when compared with untreated control areas, pre-emergence herbicide treatments did not negatively affect blackberry fruit yield, weight, or quality attributes including pH and soluble solids concentration. A study by Mennan and Ngouajio (2012) found that brassica cover crops including rape (*Brassica napus*), field mustard (*Brassica rapa*), and oriental mustard (*Brassica juncea*), effectively reduced weed density in hazelnut production systems. In grape (*Vitis* spp.) production, cover crop treatments have been shown to increase soluble solids content and anthocyanin levels in fruit, while decreasing titratable acidity and pH (Steenwerth and Guerra 2012). Cover crops in perennial systems can provide ecosystem services including soil retention, provision of pollinator habitat, weed control, improved soil physical properties, carbon sequestration, enhanced water quality, and improved nutrient cycling (Crézé et al. 2021).

Considering that weed management is a crucial component of agricultural systems and that common, as well as prospective, strategies have not been well characterized in American elderberry production, the objective of this study was to develop a foundation for weed management in American elderberry production. The specific goal of the study was to elucidate effective and practical weed management options for American elderberry production by assessing biological outcomes (plant growth, yield, fruit quality, and weed suppression) alongside economic performance (annualized net present value) on a commercial scale.

Materials and Methods

Orchards and experimental set-up. This multiyear field study was initiated in May 2022 at two University of Missouri Research Farms: Southwest Research, Extension, and Education Center (SWC) near Mt. Vernon, MO, USA (lat. 37.0747, long. -93.8789), and the Horticulture and Agroforestry Research Farm (HARF) near New Franklin, MO, USA (lat. 39.0192, long. -92.7600). Before the establishment of this study, the SWC site was managed in cool season grass pasture, and the HARF site served as a vineyard. The SWC site featured two soil series: Creldon silt loam (fine, mixed, active, mesic Oxyaquic Fragiudalfs), which is moderately well drained with a fragipan at 51 to 89 cm, and Gerald silt loam (fine, mixed, active, mesic Aeric Fragiudalfs), which is poorly drained, with a fragipan at 51 to 102 cm. Soil series at the HARF site included a Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs) and Sibley silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls), both of which are well drained loess soils with a fragipan depth greater than 203 cm (Web Soil Survey 2023).

Soil samples were collected and evaluated before planting in spring of 2022. The SWC site offered ideal growing conditions for elderberry (Byers et al. 2022), with a pH of 6.0, a cation exchange capacity of 8.4 meq/100 g, and 2.2% organic matter. Phosphorus and potassium levels were adjusted based on recommendations for bramble crops, as nutrient recommendations specific to elderberry have not been established. The HARF site was also well suited for growing elderberries, with a pH of 5.7 to 5.8, a cation exchange capacity of 12.3 to 13.8 meq/100 g, 2.6% to 3.0% organic matter, and adequate levels of P, K, Ca, and Mg. Following planting, individual plots were fertilized with 13N-13P-13K fertilizer in Jul 2022 at a rate of 67 kg·ha⁻¹. In spring of 2023 and 2024, individual plots were fertilized with urea, providing 67 and 90 kg N·ha⁻¹, respectively.

The SWC site received 1052, 1187, and 993 mm of precipitation during the 2022, 2023, and 2024 growing seasons, respectively, while HARF received 707, 711, and 1040 mm (Missouri Mesonet - AgEBB, 2024). A drip irrigation line (Netafim Irrigation, Inc., Fresno, CA, USA) was installed for each row, with emitters 61 cm apart. Plantings received up to

25 mm supplemental water per week during the growing seasons when rainfall was lacking.

Three American elderberry cultivars were selected for the study: 'Bob Gordon', 'Pocahontas', and 'Rogersville' (Byers and Thomas 2011; McGowan and Thomas 2017; Thomas et al. 2023). Dormant hardwood cuttings sourced from existing plants at the SWC were propagated in Mar 2022. Propagules were treated with Bontone II rooting powder (BONIDE Products LLC, Oriskany, NY, USA) and positioned in 10.2-cm plastic pots with commercial potting mix (Pro-Mix BX; Premier Tech, Quakertown, PA, USA) and placed in a cool greenhouse for rooting. Site preparation began in Apr 2022. Rows were formed using a tractor-mounted roto tiller, 1.5 m wide. Row centers at both sites were spaced 4.6 m apart. Seventy-two linear in-row experimental plots were established at each site. Plots were arranged in eight rows at the SWC site and four rows at HARF. Plots were 1.2 m wide by 4.9 m long, with 2.4 m between plots in-row. Each plot contained four elderberry plants of the same cultivar spaced 1.2 m apart. The alleys and in-row spaces between plots were left in existing perennial grass cover and managed via mowing and string trimming. Each of the three cultivars was assigned to 24 plots in a completely randomized design and transplanted into the orchard 18 May 2022 at SWC and 23 May 2022 at HARF. Flowers were removed in the establishment year (2022) to encourage vegetative growth and development of healthy roots. In Jan 2024, the plants were pruned, effectively removing dead or damaged plant material and tipping back canes to strong wood.

Weed management treatments. Four replications of six weed management treatments [woven fabric, woodchip mulch, cover crop, herbicide, managed (hand-weeded) control, and unmanaged control] were randomly assigned to each cultivar's 24 plots. Woven fabric plots were established at the time of planting. Dewitt Sunbelt woven weed barrier fabric (Dewitt, Sikeston, MO, USA) (0.9 m wide, 108.5 g·m⁻²) was installed in May 2022. Fabric was placed by hand and secured using metal fabric pins. A butane torch was used to burn holes 15 cm in diameter in the fabric to allow for planting. In Jan 2023, a slit was burned down the center of the fabric row within plots to allow elderberry plants space to spread and sucker naturally via rhizomes.

Woodchip mulch plots were established at the time of planting. At the SWC site mulch was sourced from the local electric cooperative and included mixed hardwood species. At HARF, mixed hardwood mulch was purchased from Braik's Tree Service (Columbia, MO, USA). Mulch was initially applied in a 10-cm-thick layer within the treatment area, followed by a 5-cm layer applied on top of existing mulch in Spring 2023 and 2024.

Cover crop plots were managed via string trimming and periodic hand weeding during the establishment season (2022). In Sep 2022, oat (*Avena sativa*) seed (Petrus Seed and Grain Co. Hazen, AR, USA) was evenly broadcast

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at a rate of $0.3 \text{ kg} \cdot \text{m}^{-2}$ and then covered with a 5-cm layer of straw; soil was not disturbed, and seed was not incorporated. Straw application was only used for the initial planting, as cover crop residue was present thereafter. Oats did not winter kill and were allowed to naturally end in Jun 2023. In Jul 2023, the remaining oat residue was cut with a string trimmer, and buckwheat (*Fagopyrum esculentum*) seed (Big Sky Wholesale Seeds, Inc. Shelby, MT, USA) was evenly broadcast over each plot at a rate of $0.3 \text{ kg} \cdot \text{m}^{-2}$. In Oct 2023, buckwheat ended naturally, residue was cut with a string trimmer, and then oats were immediately broadcast at the same rate. Once again, the oats did not winter kill, and similar protocols were used to re-establish buckwheat in Summer 2024.

Herbicide plots were managed via string trimming and periodic hand weeding during plot establishment in 2022. In Mar 2023 and 2024, existing vegetation was removed using glufosinate (Reckon 280SL; Solera, Yuma, AZ, USA), a postemergence, broad spectrum contact herbicide which was applied at $4.1 \text{ L} \cdot \text{ha}^{-2}$ using a backpack sprayer. Four additional applications of glufosinate were used during the growing seasons both years. Dichlobenil (Casoron 4G; OHP, Inc., Morrisville, NC, USA), a broad-spectrum, pre-emergence granular herbicide, was also evenly distributed by hand within each plot at $112 \text{ kg} \cdot \text{ha}^{-1}$ in Mar 2023 and 2024.

Managed (hand-weeded) plots were kept weed-free through hand weeding and hoeing at biweekly intervals throughout the study. Unmanaged control plots were maintained via string trimming and periodic hand weeding during the establishment period until Jan 2023. Thereafter, weeds were left unmanaged throughout the 2023 and 2024 growing seasons.

Experimental data collection. Phenological data (50% budbreak, 50% anthesis, and peak fruit ripening) were collected in 2023 and 2024 by documenting the date (days after 1 Jan) at which each plot exhibited the designated phenological event. Plant growth per plot was assessed at the conclusion of the growing seasons in Dec 2023 and 2024. Average plant height, maximum plant height, and stem counts were determined.

Arthropod pest, disease, and lodging pressure were determined monthly from May through August in 2023 and 2024. The 1 to 5 rating scale described by Thomas et al. (2015) was adapted to quantify damage associated with pests, diseases, and lodging (where 1 = no damage present; 2 = $\leq 25\%$ of plot damaged; 3 = 25% to 50% of plot damaged; 4 = 50% to 75% of plot damaged; and 5 = 75% to 100% of plot damaged). The ratings were documented for sawfly (*Tenthredo grandis*), Japanese beetle (*Popillia japonica*), eriophyid mite [most likely *Phyllocoptes wisconsinensis* (Warmund and Amrine 2015)], and leaf spot (undiagnosed as to specific organisms).

Fruit harvests were conducted twice weekly in 2023 and 2024 from late July through early September. Entire infructescences (cymes) were harvested when the majority of berries therein were fully ripe. Fruit yield data included total cyme fresh weight per plot, number of cymes per plot, and average

cyme weight. Representative fully ripe fruit samples (0.5 kg) from each plot were retained in zippered plastic bags and immediately frozen. The berries were later de-stemmed while frozen. Two randomly selected subsamples of 50 berries were weighed from each sample to determine mean single berry weight.

Juice sample preparation. Juice was prepared by allowing fruit to thaw, pressing by hand, and pouring through a kitchen sieve into a glass beaker. Samples were then aliquoted into polypropylene tubes and stored at -18°C until laboratory analysis. Juice samples were used to quantify soluble solids concentration, pH, titratable acidity (TA), total polyphenol concentration, and total monomeric anthocyanin concentration. Methods used for fruit analysis were adapted from Thomas et al. (2024), with the following modifications: pH was measured with an Oakton pH700 meter (2023) and an Oakton pH 5+ meter (2024) (Oakton Instruments migrated to Environmental Express, Charleston, SC, USA). For total polyphenols and total monomeric anthocyanin content, a Cary 60 ultraviolet-visible spectrophotometer (Agilent Instruments, Santa Clara CA, USA) was used in 2023, and a Multiskan SkyHigh Microplate Spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA, USA) was used in 2024.

Leaf nitrogen. Leaf nitrogen content was measured at both sites in 2023 and 2024 to evaluate nitrogen availability as an effect of weed management treatment. In July, a sample of eight to ten leaves including leaflet blades, rachis, and petioles was randomly collected from each research plot. Leaf samples were dried, ground to $<1 \text{ mm}$, and analyzed at the University of Missouri's Soil and Plant Testing Laboratory to determine total leaf nitrogen content (%) by the combustion method (Jaroonchon et al. 2010).

Weed population and visual rating. Weed species and weed population were assessed in Aug 2023 and 2024. Two 0.25-m^2 quadrats were randomly placed in each plot, weed species were identified, and the number of each individual weed species was determined. Species were categorized as annual grass, annual broadleaf, or perennial weeds. A visual rating was conducted concurrently with weed population measurements (Brown and Tworowski 2004; Burkhard et al. 2009). Data from 0.25-m^2 quadrat samples were extrapolated to represent the number of weed plants/ m^2 . A single visual rating between 0 and 100 was assigned to each plot, indicating the percentage of area in each plot covered by actively growing weed vegetation. The same individual conducted all visual ratings.

Weed biomass. A weed biomass assessment was also conducted in Aug 2023 and 2024, using methods adapted from Burkhard et al. (2009). Weed biomass from the two 0.25-m^2 quadrat samples used for species and population measurements was harvested at ground level, separated into the three botanical categories, and placed in brown paper bags. Samples were then dried in industrial dryers at 40°C until reaching a constant weight and then weighed to determine the dry weight of biomass (Zhang et al. 2019). Data from 0.25-m^2 quadrat samples were

extrapolated to represent dry weight of weed biomass in $\text{g} \cdot \text{m}^{-2}$.

Economic analysis. A partial budget analysis was used to compare differences in costs, revenue, and profitability among treatments. The analysis was considered deterministic as no stochastic variables were included. Although yield is theoretically stochastic due to factors such as weather, in our analysis it was treated as deterministic because we used observed experimental mean yields rather than simulated yield distributions. Methods used in developing the partial budget analysis were adapted from those described by Skevas et al. (2016). Costs that remained constant across weed management treatments (i.e., irrigation) were not included in the analysis. Only costs that varied among treatments were included in the model. Costs were separated into two categories. Labor costs, documented in US dollars per hour, accounted for variability in labor requirements among treatments. Hourly wage was assumed to be \$17.26 (Missouri Economic Research and Information Center 2023). Materials and equipment costs were also documented for each treatment. Revenue was estimated using the mean fruit yield for each treatment combination and a farmgate price of \$5/0.454 kg (1-pound) of fresh, de-stemmed berries (Byers et al. 2022). Data collected in the weed management study were extrapolated to represent a 0.405-ha (1-acre) commercial elderberry planting based on current spacing and plant population recommendations: ~ 1678 plants/ha (679 plants/acre). The values were converted to net present value (NPV) using the following formula:

$$\text{NPV}_{\text{sm}} = \sum_{t=1}^3 \frac{R_{\text{smt}} - C_{\text{smt}}}{(1+r)^t} \quad [1]$$

where R and C stand for revenues and costs, respectively, for each site (s), weeding method (m), and period (t). Following Erickson et al. (2004), a discount rate (r) of 5% was used, which is consistent with previous economic assessments in perennial crops (Kells and Swinton 2014; Skevas et al. 2016). NPVs were annualized by dividing them by an annuity factor, reflecting the present value of receiving (or paying) a constant amount each year for 3 years at the given discount rate (Predo and James 2006; Weston and Copeland 1986). Annualizing the NPV expresses the multiyear value as an equivalent constant annual return, providing a common scale for comparison across treatments and aligning with standard practices in agricultural economic assessments (El Kasmioui and Ceulemans 2012; Kells and Swinton 2014; Skevas et al. 2016). The annuity factor is given by:

$$\text{AF} = \frac{1 - (1+r)^{-t}}{r} \quad [2]$$

Then, the annualized NPV for each treatment at each site is computed as:

$$\text{Annualized NPV}_{\text{sm}} = \frac{\text{NPV}_{\text{sm}}}{\text{AF}} \quad [3]$$

This annualized NPV serves as a summary measure of each weeding method's economic

performance over time, at each of the two sites.

Statistical analysis. The experiment was established and analyzed as a factorial experiment with a completely randomized design. Factors included 2 sites $\times$ 3 cultivars $\times$ 6 weed management treatments $\times$ 4 plot replications, with year (2023–24) serving as a repeated measure over time. The experimental unit was the 1.2-m-wide by 4.9-m-long orchard plot, each containing four elderberry plants of the same cultivar. Site served as an independent random factor, while weed management method and cultivar were designated as independent fixed factors. All data aside from those in the economic analysis were analyzed using the MIXED procedure (SAS Institute, Cary, NC, USA), with means separated by the Tukey's honestly significant difference (HSD) method at $P < 0.05$.

To compare mean NPVs across treatments, a one-way analysis of variance (ANOVA) was conducted. This procedure not only provides a global test of whether there are significant differences across treatments but also avoids accumulating type I errors from multiple t tests (Ender 2016). If the F test was significant, *post hoc*, pairwise comparisons between treatments were performed using Tukey's HSD test (Ender 2016; StataCorp 2025a). However, because annualized NPVs may not only differ in terms of their means but of their entire distributions (e.g., shape, spread, or location), two-sample Kolmogorov–Smirnov tests were also performed to detect distributional dominance of one treatment over the other across the entire range (Conover 1999; StataCorp 2025b).

Results and Discussion

The elderberry plantings at both sites established and performed well during the study period. Weed management treatment had a notable influence on elderberry plant growth, date of flowering, peak fruit ripening, fruit yield characteristics, pest incidence, disease, lodging damage, weed ecology, and profitability. Weed management treatments had no significant effects on budbreak and certain fruit quality parameters.

Phenology and plant growth. Phenological variables were influenced by year and cultivar (Table 1). Weed management treatment had no effect on budbreak but did influence the date of flowering and peak fruit ripening (Table 1). Cover crop, unmanaged control, and herbicide plots presented flowering dates significantly later than all other weed management treatments at 165.2, 164.3, and 162.0 d after 1 Jan, respectively (14 Jun, 13 Jun, and 10 Jun). All other treatments fell between 160 and 161 d (8 and 9 Jun). Peak fruit ripening fell between 220 and 225 d after 1 Jan (9 and 14 Aug). The woven fabric treatment offered the earliest fruit ripening at 220.1 d, while the unmanaged control was significantly later at 224.5 d. Further research is necessary to understand the potential effect of various cover crop species on American elderberry phenology.

Both cultivar and weed management treatment had an effect ($P < 0.0001$) on percent total leaf N (Table 1). The leaf N value for the herbicide treatment (2.84%) was significantly greater than that of all other treatments. The woven fabric and unmanaged control treatments contained the lowest values at 2.14% and 2.12% leaf N, respectively. The woven fabric treatment may have resulted in lower values due to the physical barrier preventing granular N fertilizer from immediately and evenly reaching the elderberry root zone (Zibilske 2010). Woodchip mulch did not have a notable negative impact on leaf N content as might have been expected. While incorporated woody materials can create zones of N deficiency, applying woodchip mulch to the soil surface may not immediately result in significant N mobilization or crop growth suppression. Studies have shown that N assimilation can occur at the mulch/soil interface but have no influence on established roots below the soil surface (Chalker-Scott 2007; Greenly and Rakow 1995).

Elderberry growth measurements were influenced by year, cultivar, and weed management treatment (Table 1). Maximum plant height increased by 0.2 m from 2023–24. Weed management treatment had a significant effect ($P < 0.0001$) on maximum plant height, with managed control and woodchip mulch treatments offering the greatest values at 1.6 and 1.5 m, respectively. A similar trend was observed in average plant height measurements. The managed control, woodchip mulch, and woven fabric treatments presented the greatest values for average height at 1.2, 1.2, and 1.1 m, respectively. Woodchip mulch, managed control, and woven fabric treatments offered stem counts of 11.2, 8.8, and 8.0, respectively, all of which were greater than the unmanaged control at 5.4 stems/plot. Competition from both weed and cover crop species likely had a negative impact on plant growth within the cover crop treatment (Fleishman et al. 2023).

Fruit yield characteristics. Both year and cultivar had a significant influence on fruit yield characteristics (Table 2). Across both years, weed management treatment also influenced fruit yield ($P < 0.0001$), with the managed control having the greatest cumulative yield at 3.9 kg/plot (plot = 5.9 m²). The herbicide, mulch, and woven fabric treatments were not significantly different from the managed control, producing yields of 3.4, 3.3, and 2.7 kg/plot, respectively. The cover crop treatment produced an average yield of 1.1 kg/plot, which was significantly less than all other treatments aside from the unmanaged control (0.7 kg/plot). A significant year $\times$ treatment interaction was observed. More specifically (data not shown), in 2023, the greatest yield was found in the managed control (3.4 kg/plot), followed by woodchip mulch (2.5 kg/plot) and woven fabric (2.0 kg/plot), which were all statistically similar. In 2024, both herbicide and woodchip mulch treatments produced numerically greater yields, but the results were not statistically different from the managed control (4.3 kg/plot) at 4.8 and 4.7 kg/plot, respectively.

The woven fabric treatment yield was not statistically less than the managed control at 2.9 kg/plot. Weed management treatment also influenced cyme number ($P < 0.0001$), with mulch, managed control, woven fabric, and herbicide plots presenting the greatest values. Total cyme number for the mulch treatment was numerically greater than that of the managed control, but these results were not statistically different. Greater cyme numbers in the mulch treatment may be associated with a greater number of stems per plot. Significant differences ($P = 0.0005$) in cyme weight were observed among weed management treatments, with herbicide, managed control, mulch, and woven fabric plots presenting the greatest average cyme weights. Differences ($P < 0.0001$) in mean single berry weight were also observed among weed management treatments with herbicide, cover crop, managed control, and mulch treatments producing the greatest berry weights. Woven fabric and unmanaged control plots offered significantly lower values for mean single berry weight. Herbicide, mulch, and woven fabric treatments were generally not statistically different from the managed control in terms of fruit yield characteristics. Aside from the managed control, the herbicide treatment offered the greatest numeric values for cumulative fruit yield, average cyme weight, and mean single berry weight. Competition from weed and cover crop species likely limited fruit yield in the cover crop treatment (Fang et al. 2022).

Fruit quality analysis. Weed management treatment had no influence on soluble solid concentration, total polyphenol concentration, or total monomeric anthocyanin concentration (data not shown) but did affect pH and TA (Table 2). Year and cultivar effects were observed in all parameters excluding total monomeric anthocyanins. While limited separation is observed among weed management treatments, fruit from the herbicide treatment had a pH of 4.63, which was significantly higher than that of the managed control, woven fabric, and cover crop treatments at 4.47, 4.45, and 4.45, respectively. Higher juice pH is considered undesirable for both processing and winemaking. The herbicide treatment offered a TA significantly lower than that of both woodchip mulch and cover crop treatments. Additional research may be necessary to elucidate the effect of weed management treatment on pH and TA of American elderberry fruit.

Pest, disease, and lodging rating scale. Weed management treatment had a significant effect on all four pest and disease ratings (Table 3). Cover crop, managed, unmanaged, and woven fabric treatments presented higher levels of sawfly damage, while ratings were significantly lower in both woodchip mulch and herbicide plots. While little separation was observed among treatments in terms of Japanese beetle damage, rankings in herbicide plots were significantly lower than those of the unmanaged control. Greater amounts of vegetation surrounding plants in unmanaged and cover crop treatments may explain the increased levels of Japanese beetle damage in these plots (Szendrei and Isaacs 2006).

Table 1. Effect of year, cultivar, and weed management treatment on American elderberry plant growth, phenology, and leaf nitrogen content across two Missouri research sites, 2023–24.

Factor	Subfactor	Budbreak (day of yr) ⁱ	Flowering (day of yr)	Peak ripening (day of yr)	Total leaf nitrogen (%)	Max ht (m)	Avg ht (m)	Stem count (no.)
Year	2023	50.0 b ⁱⁱ	166.8 a	229.4 a	2.35	1.3 b	0.9 b	7.7
	2024	52.0 a	157.9 b	215.1 b	2.40	1.5 a	1.2 a	8.0
		$P = 0.0053$	$P < 0.0001$	$P < 0.0001$	$P = 0.0952$	$P < 0.0001$	$P < 0.0001$	$P = 0.9258$
Cultivar	Bob Gordon	49.0 b	157.3 c	213.0 c	2.61 a	1.4	1.1 a	10.7 a
	Pocahontas	50.0 b	166.8 a	225.4 b	2.15 c	1.4	1.1 ab	7.1 b
	Rogersville	54.0 a	163.1 b	228.4 a	2.37 b	1.3	1.0 b	5.8 c
		$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.3479$	$P = 0.0021$	$P < 0.0001$
Treatment	Woven fabric	50.6	160.8 c	220.1 b	2.14 c	1.4 bc	1.1 abc	8.0 abc
	Mulch	50.9	161.1 bc	221.3 ab	2.39 b	1.5 ab	1.1 ab	11.2 a
	Cover crop	51.3	165.2 a	224.0 ab	2.40 b	1.2 cd	1.0 c	6.3 cd
	Herbicide	51.5	162.0 abc	223.4 ab	2.84 a	1.4 bc	1.0 bc	7.5 bcd
	Managed control	50.9	161.0 bc	220.2 b	2.38 b	1.6 a	1.2 a	8.8 ab
	Unmanaged control	50.9	164.3 ab	224.5 a	2.12 c	1.1 d	0.9 c	5.4 d
		$P = 0.931$	$P = 0.0002$	$P = 0.0029$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Interaction ⁱⁱⁱ	Y × C	$P = 0.1831$	$P < 0.0001$	$P = 0.8248$	$P = 0.2423$	$P = 0.2566$	$P = 0.0028$	$P = 0.8686$
	Y × T	$P = 0.937$	$P = 0.3693$	$P = 0.4755$	$P = 0.0001$	$P = 0.5673$	$P = 0.0508$	$P = 0.0024$
	C × T	$P = 0.9403$	$P = 0.9459$	$P = 0.6835$	$P = 0.3935$	$P = 0.5914$	$P = 0.8802$	$P = 0.1695$
	Y × C × T	$P = 0.9998$	$P = 0.6103$	$P = 0.6234$	$P = 0.8583$	$P = 0.748$	$P = 0.5546$	$P = 0.0962$

ⁱDay of year = days from 1 Jan.ⁱⁱMeans within subcolumns with the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).ⁱⁱⁱC = cultivar; T = treatment; Y = year.

An opposite trend was observed with eriophyid mite damage. Herbicide and managed control plots exhibited mite damage that was significantly greater than that of the unmanaged control. Eriophyid mites are known to disperse via wind (Michalska et al. 2010). It is suspected that the vegetation associated with cover crop and unmanaged control plots may serve as a buffer, reducing mite populations and associated damage, or it may generally be creating a microenvironment less conducive to the mites. In terms of leaf spot, the woven fabric and managed control treatments presented values significantly greater than that of the cover crop treatment. Incidence of lodging was found to be most severe in managed control and herbicide treatments; the bare soil conditions associated with these

treatments may encourage stems to lodge more easily.

Visual weed cover rating and weed population. Dominant weed species at the HARF site included Carolina horsenettle (*Solanum carolinense*), field bindweed (*Convolvulus arvensis*), yellow nutsedge (*Cyperus esculentus*), dandelion (*Taraxacum officinale*), marestail (*Erigeron canadensis*), and large crabgrass (*Digitaria sanguinalis*). Dominant weeds at the SWC site included buckhorn plantain (*Plantago coronopus*), dandelion, common ragweed (*Ambrosia artemisiifolia*), white heath aster (*Symphotrichum ericoides*), and large crabgrass. Cultivar had no significant effect on visual weed cover ratings or weed population measurements (Table 4). Visual ratings of weed coverage in August increased by 4.2%

between 2023 and 2024. The unmanaged control presented the greatest visual rating with 92% coverage. Woodchip mulch and herbicide treatments resulted in reduced visual ratings, both falling between 24% and 26%. In terms of total weed population, the unmanaged control offered the greatest value (84.4 weed plants/m²). Herbicide plots had the second highest value with a total population of 45.2 weed plants/m². While the herbicide treatment did have a greater weed population, pairing these results with visual ratings and weed biomass measurements in August indicates that weeds were densely populated but not large enough to contribute to increased visual ratings. Woodchip mulch offered the lowest total weed population (17.6) aside from the managed control. Annual grass population densities for woven fabric and cover crop

Table 2. Effect of year, cultivar and weed management treatment on American elderberry fruit yield characteristics and fruit quality parameters across two Missouri research sites, 2023–24.

Factor	Subfactor	Yield (kg/plot) ⁱ	Cymes (number/plot)	Mean cyme wt (g)	Mean single berry wt (mg)	pH	TA (g/100 ml citric acid) ⁱⁱ
Year	2023	1.8 b ⁱⁱⁱ	48.6 b	39.4 b	79.5 a	4.42 b	0.49 b
	2024	3.2 a	71.6 a	45.9 a	62.7 b	4.61 a	0.68 a
		$P < 0.0001$	$P < 0.0001$	$P = 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Cultivar	Bob Gordon	2.7 a	87.7 a	28.8 b	74.9 a	4.48 b	0.58 ab
	Pocahontas	3.3 a	47.3 b	66.1 a	67.7 b	4.58 a	0.55 b
	Rogersville	1.5 b	45.4 b	33.1 b	70.6 b	4.50 ab	0.63 a
		$P < 0.0001$	$P < 0.0001$	$P = 0.0002$	$P < 0.0001$	$P = 0.0207$	$P = 0.0079$
Treatment	Woven fabric	2.7 a	79.7 a	42.6 ab	63.3 b	4.45 c	0.58 ab
	Mulch	3.3 a	86.5 a	43.0 ab	72.4 ab	4.58 ab	0.63 a
	Cover crop	1.1 b	26.5 b	34.4 bc	74.0 a	4.45 bc	0.64 a
	Herbicide	3.4 a	60.0 a	63.2 a	79.3 a	4.63 a	0.53 b
	Managed control	3.9 a	84.2 a	52.9 a	73.0 a	4.47 bc	0.57 ab
	Unmanaged control	0.7 b	23.9 b	20.0 c	64.6 b	4.52 abc	0.56 ab
		$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.001$	$P = 0.01$
Interaction ^{iv}	Y × C	$P = 0.0218$	$P = 0.1174$	$P = 0.3009$	$P = 0.0008$	$P = 0.0425$	$P = 0.5896$
	Y × T	$P < 0.0001$	$P = 0.0005$	$P = 0.0202$	$P = 0.7624$	$P = 0.6511$	$P = 0.6245$
	C × T	$P = 0.7085$	$P = 0.9736$	$P = 0.6452$	$P = 0.3294$	$P = 0.7607$	$P = 0.9872$
	Y × C × T	$P = 0.9475$	$P = 0.9686$	$P = 0.7185$	$P = 0.7728$	$P = 0.8851$	$P = 0.9857$

ⁱPlot size: 1.2 m × 4.9 m (5.9 m²).ⁱⁱTA = titratable acidity.ⁱⁱⁱMeans within subcolumns with the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).^{iv}C = cultivar; T = treatment; Y = year.

Table 3. Effect of year, cultivar, and weed management treatment on American elderberry rankings for pest, disease, and lodging damage across two Missouri research sites, 2023–24.

Factor	Subfactor	Sawfly	Japanese beetle	Eriophyid mite	Leaf spot	Lodging
Year	2023	1.9 ⁱ	1.4 a	1.5	1.8 b	1.2 b
	2024	1.9	1.3 b	1.4	2.1 a	1.4 a
Cultivar		$P = 0.8689$	$P = 0.0269$	$P = 0.269$	$P < 0.0001$	$P = 0.0072$
	Bob Gordon	2.0 a ⁱⁱ	1.2 b	1.5 b	1.8	1.2 b
	Pocahontas	2.0 ab	1.8 a	1.1 c	1.9	1.5 a
	Rogersville	1.8 b	1.2 b	1.8 a	2.0	1.2 b
Treatment		$P = 0.0162$	$P < 0.0001$	$P < 0.0001$	$P = 0.6392$	$P = 0.0004$
	Woven fabric	1.9 abc	1.5 ab	1.3 ab	2.2 ab	1.2 b
	Mulch	1.8 bc	1.3 ab	1.6 ab	1.9 abc	1.2 b
	Cover crop	2.0 ab	1.4 ab	1.4 ab	1.7 c	1.1 b
	Herbicide	1.6 c	1.3 b	1.6 a	1.7 bc	1.6 a
	Managed control	2.0 ab	1.3 ab	1.6 a	2.3 a	1.6 a
	Unmanaged control	2.2 a	1.6 a	1.2 b	1.7 bc	1.0 b
Interaction ⁱⁱⁱ		$P < 0.0001$	$P = 0.0392$	$P = 0.0047$	$P = 0.0005$	$P < 0.0001$
	Y × C	$P = 0.0504$	$P = 0.178$	$P = 0.2162$	$P = 0.0452$	$P = 0.1509$
	Y × T	$P = 0.1323$	$P = 0.5798$	$P = 0.3329$	$P = 0.1875$	$P = 0.0053$
	C × T	$P = 0.2884$	$P = 0.7515$	$P = 0.1923$	$P = 0.7632$	$P = 0.0388$
	Y × C × T	$P = 0.4250$	$P = 0.8715$	$P = 0.5336$	$P = 0.8533$	$P = 0.0805$

ⁱPest and Disease Rating Scale: 1 = no damage present; 2 = <25% of plot damaged; 3 = 25% to 50% of plot damaged; 4 = 50% to 75% of plot damaged; 5 = 75% to 100% of plot damaged.

ⁱⁱMeans within subcolumns with the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).

ⁱⁱⁱC = cultivar; T = treatment; Y = year.

treatments were not significantly different from the unmanaged control. In terms of annual broadleaf population, the value observed in the herbicide treatment was not significantly different from the unmanaged control. Woodchip mulch offered the lowest value aside from the unmanaged control with an average of 1.2 annual broadleaf weed plants/m². The herbicide, mulch, and woven fabric treatments resulted in the lowest perennial weed densities aside from the managed control. In general, woodchip mulch was most effective in reducing weed population and visual ratings in August.

The herbicide treatment also offered a low visual ratings but presented greater weed density due to high populations of small weeds associated with recurring herbicide applications.

Weed biomass. A significant increase in both total weed biomass and annual grass biomass was found between 2023 and 2024 (Table 4). Cultivar had no influence on weed biomass measurements, while weed management treatment had a significant influence ($P < 0.0001$) on all measurements. As expected, the unmanaged control had the highest total weed biomass dry weight at 419.6 g·m⁻². Woven fabric and cover crop plots presented

values of 235.2 and 119.2 g·m⁻², respectively. Mulch and herbicide plots offered the lowest values aside from the managed control at 60.0 and 39.6, respectively. Annual grass biomass in the woven fabric treatment (98.0 g·m⁻²) was numerically greater than all other treatments and statistically greater than mulch (14.0), herbicide (8.0), and the managed control (0.0). Excluding the unmanaged control, the greatest annual broadleaf biomass was observed in the woven fabric treatment with 58.8 g·m⁻². Measurements for remaining treatments were significantly lower, falling between 0.0 and 12.0 g·m⁻². Higher levels of

Table 4. Effect of year, cultivar, and weed management treatment on weed cover visual ratings, weed population, and dry weed biomass across two Missouri research sites, 2023–24.

Factor	Subfactor	Visual rating ⁱ	Total		Annual grass		Annual broadleaf		Perennial	
			Population ⁱⁱ	Biomass ⁱⁱⁱ	Population	Biomass	Population	Biomass	Population	Biomass
Year	2023	33.7 b ^{iv}	39.2 a	133.2 b	15.6 a	26.8 b	6.8	55.6	16.8 a	50.4
	2024	37.9 a	30.4 b	158.0 a	8.4 b	40.0 a	10.4	46.8	10.8 b	71.2
Cultivar		$P = 0.0013$	$P = 0.0374$	$P = 0.0011$	$P = 0.0003$	$P < 0.0001$	$P = 0.2611$	$P = 0.3157$	$P < 0.0001$	$P = 0.3041$
	Bob Gordon	35.4	33.2	123.2	10.8	19.2	7.6	36.0	14.8	68.0
	Pocahontas	34.6	32.8	149.6	12.0	30.8	8.0	56.0	12.8	62.8
	Rogersville	37.5	38.4	163.2	12.8	50.4	10.0	61.2	13.6	52.0
Treatment		$P = 0.3612$	$P = 0.4571$	$P = 0.1396$	$P = 0.7070$	$P = 0.6363$	$P = 0.0711$	$P = 0.1226$	$P = 0.9629$	$P = 0.5825$
	Woven fabric	33.4 bc	26.4 b	235.2 b	12.0 a	98.0 a	4.8 b	58.8 b	9.6 c	77.6 b
	Mulch	25.8 cd	17.6 c	60.0 c	6.0 b	14.8 b	1.2 c	12.0 c	10.8 bc	33.2 bc
	Cover crop	38.6 b	35.2 b	119.2 b	12.0 a	44.8 a	8.0 bc	10.8 c	15.6 ab	63.2 b
	Herbicide	24.8 d	45.2 b	39.6 c	3.2 b	8.0 b	17.6 a	12.0 c	24.4 abc	19.6 c
	Managed control	0.0 e	0.0 d	0.0 d	0.0 c	0.0 c	0.0 d	0.0 d	0.0 d	0.0 d
	Unmanaged control	92.3 a	84.4 a	419.6 a	38.4 a	34.8 a	20.4 a	213.2 a	22.0 a	171.6 a
Interaction ^v		$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
	Y × C	$P = 0.2867$	$P = 0.5089$	$P = 0.1703$	$P = 0.1262$	$P = 0.108$	$P = 0.6953$	$P = 0.2783$	$P = 0.3342$	$P = 0.7886$
	Y × T	$P < 0.0001$	$P = 0.0023$	$P = 0.0002$	$P = 0.0002$	$P = 0.0061$	$P = 0.1105$	$P = 0.5128$	$P = 0.0004$	$P = 0.005$
	C × T	$P = 0.59$	$P = 0.5119$	$P = 0.8155$	$P = 0.3175$	$P = 0.3427$	$P = 0.8356$	$P = 0.069$	$P = 0.7731$	$P = 0.5145$
	Y × C × T	$P = 0.8407$	$P = 0.3291$	$P = 0.2269$	$P = 0.9456$	$P = 0.1559$	$P = 0.8108$	$P = 0.1511$	$P = 0.9466$	$P = 0.6793$

ⁱVisual rating: Visual estimation of percent of plot covered by actively growing weed vegetation.

ⁱⁱPopulation: Total number of weed plants/m². Extrapolated from 0.25-m² samples.

ⁱⁱⁱBiomass: Weight of dry weed biomass (g·m⁻²). Extrapolated from 0.25-m² samples.

^{iv}Means within subcolumns with the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).

^vC = cultivar; T = treatment; Y = year.

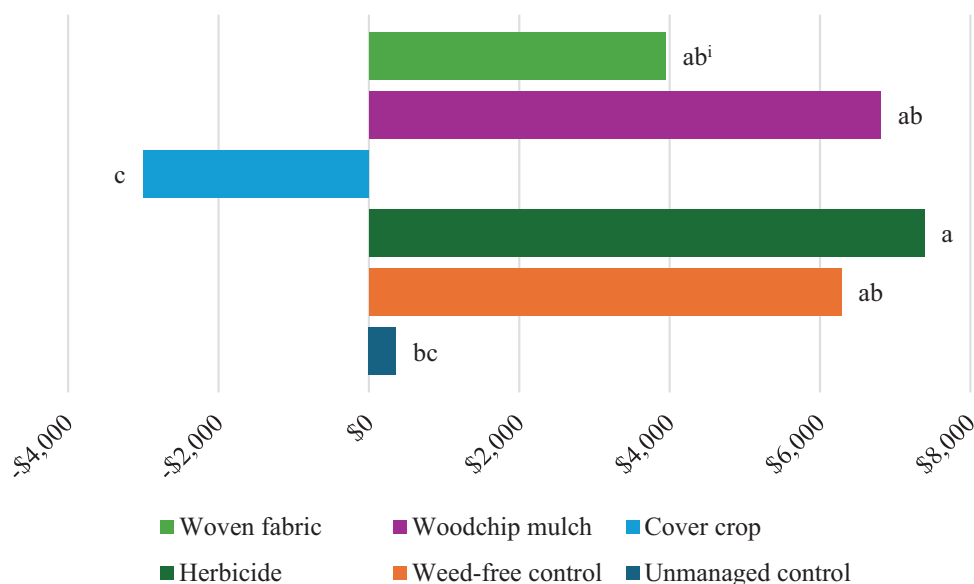


Fig. 1. Effect of weed management treatment on annualized net present value of profit (\$/ha) in American elderberry production systems across three cultivars and 3 years (2022–24) at the University of Missouri's Horticulture and Agroforestry Research Farm. ⁱ Treatments sharing the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).

perennial weed biomass were found in woven fabric and cover crop treatments, with 77.6 and 63.2 g·m⁻², respectively. The herbicide treatment offered effective perennial weed suppression, with a dry weed biomass measurement of 19.6 g·m⁻². Overall, mulch and herbicide treatments provided the greatest reduction of dry weed biomass in August aside from the managed control.

Economic analysis. Figure 1 displays the annualized NPVs (in dollars per hectare) for the weed management practices evaluated at the HARF site, while Fig. 2 presents the corresponding values for the SWC site. (summary of statistics provided in Supplemental Table 1). Annualized NPV provides a standardized measure of average annual profitability by

accounting for the timing and magnitude of costs and returns over the duration of each treatment. It enables direct comparison across weed management strategies and sites with varying economic conditions.

Some differences in NPV were observed between the two locations. With the exception of the weed-free control, all treatments exhibited higher annualized NPVs at SWC compared with HARF. Notably, woven fabric emerged as the most profitable treatment at SWC, with an annualized NPV exceeding \$8700 per hectare. In contrast, the woven fabric treatment underperformed at HARF, resulting in an annualized NPV of about \$3945, which was less than that of woodchip mulch, herbicide, and the weed-free control. Across

both sites, cover crop and the unmanaged control consistently showed the lowest economic performance, with the cover crop treatment yielding negative annualized NPVs at both locations.

Further insight into these differences comes from examining the breakdown of revenues and production costs (Supplemental Figs. 1 and 2). The cost structures were broadly consistent across sites, with labor and material expenses following similar patterns. Differences in annualized NPV were driven more by yield variation than by costs. For example, the cover crop treatment combined relatively high costs (second only to the labor-intensive weed-free control) with the lowest yields (apart from the unmanaged control), leading to negative

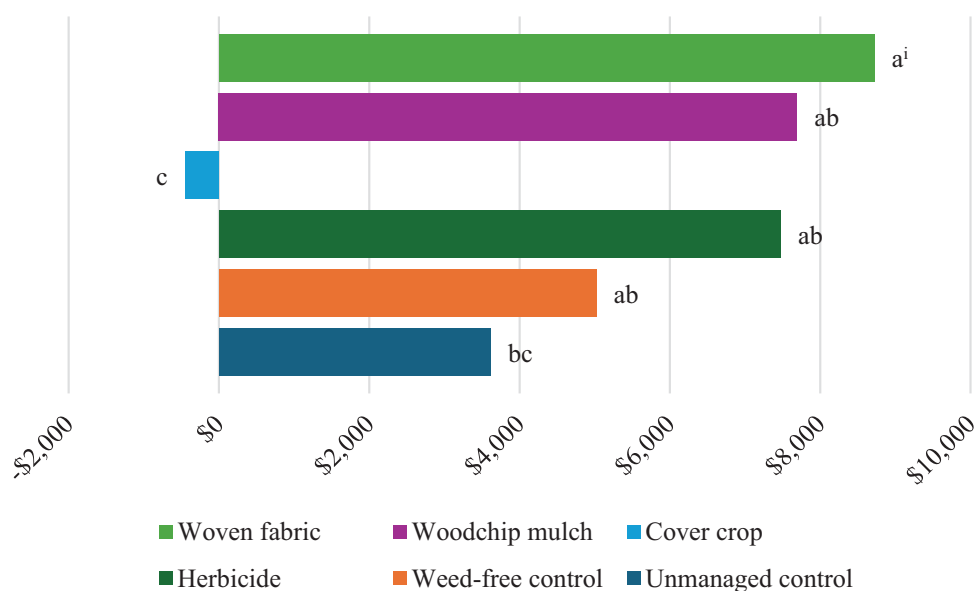


Fig. 2. Effect of weed management treatment on annualized net present value of profit (\$/ha) in American elderberry production systems across three cultivars and 3 years (2022–24) at the University of Missouri's Southwest Research, Extension, and Education Center. ⁱ Treatments sharing the same letters are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$).

profits. In contrast, herbicide and woodchip mulch paired moderate costs with strong revenues, producing the highest profits. Woven fabric overperformed at SWC, where yields were substantially higher than at HARF, highlighting that yield differences were the dominant factor explaining site-level NPV outcomes.

To assess the statistical significance of the observed differences in annualized NPVs, one-way ANOVA, Tukey's HSD test, and two-sample Kolmogorov–Smirnov tests were performed. All tests revealed consistent results. The ANOVA (Supplemental Tables 2 and 3) showed significant differences in mean annualized NPVs among treatment groups at both sites ($P > F = 0.000$), explaining ~30% of the variance (adjusted R^2 values of 0.286 for HARF and 0.330 for SWC). Post-hoc Tukey HSD comparisons (Supplemental Table 4 and 5) further confirmed that herbicide, woodchip mulch, woven fabric, and the weed-free control had significantly higher NPVs than the cover crop, with mean differences ranging from \$5468 to \$10,388 ($P < 0.05$ or $P < 0.01$).

In addition, the two-sample Kolmogorov–Smirnov tests (Supplemental Tables 6 and 7) supported these findings, showing that the distribution of NPVs for cover crop was dominated by all other treatments. Similarly, the unmanaged control was dominated by herbicide, woodchip mulch, and woven fabric at both sites and by the weed-free control at HARF. These tests suggest that the dominant treatments consistently produced higher NPVs across both sites, with the variability between sites indicating potential environmental influences.

Conclusions

The results of this study highlight the responsiveness of cultivated American elderberry to management conditions. Compared with the unmanaged control, applied weed management treatments had a positive influence on both plant performance and economic outcomes. Woodchip mulch and herbicide treatments offered significant weed suppression, improved plant performance, and were the most economically efficient, with consistently higher annualized NPV. Woven fabric, while the most profitable at SWC, underperformed at HARF, suggesting that its effectiveness may depend on environmental or managerial factors. Reducing the size of openings in the woven fabric treatment may offer improved plant performance and decreased weed pressure while still allowing elderberry plants to produce new shoots. It may also be beneficial to delay opening the fabric until the elderberry plants are better established and more likely to produce new shoots. The cover crop treatment consistently showed poor economic performance, indicating that adjustments in its management (i.e., seeding rate, species, and/or termination method) are needed to make it more viable. Considering the positive performance of the herbicide treatment, evaluation of additional products (both synthetic and organic) labeled for use in elderberry is warranted. Assessment

of treatment combinations (i.e., woodchip mulch with herbicide application) would also provide valuable information relative to integrated weed management. Further research is required to better understand the suitability of weed management options over the life of an elderberry planting and in expanded growing conditions.

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