Comparative Feasibility Analysis of Mechanized Equipment for Vineyard Operations

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ABSTRACT. Increasing labor and input costs have driven wine grape (Vitis vinifera) growers’ attention to mechanized equipment to assist in vineyard operations. This study evaluates the financial feasibility of investing in vineyard mechanization, in addition to the released intelligent sprayer in hypothetical wine grape vineyards of varying sizes. Our comparative analysis illustrates how mechanization of vineyard practices affects costs and financial metrics. We conducted a cost–benefit analysis for seven investment scenarios and examined the economic performance of four metrics. Our findings suggest that investing in a mechanized trimmer is most effective for growers exposed to labor shortages and high wages. A retrofitted intelligent sprayer is superior for reducing input use and associated costs.

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Recent worldwide occurrences such as the COVID-19 pandemic and the Russia–Ukraine war, in addition to environmental challenges to producing specialty crops, have led growers to evaluate mechanization alternatives. That is true for wine grapes (Vitis vinifera) in the United States, particularly in the midwestern states, where environmental conditions are not as favorable as in California’s Central Valley.

A collateral effect of the pandemic was a considerable reduction in labor supply for farm jobs. Wages have increased considerably, and wine grape growers must spend significant amounts to fill seasonal positions (Charlton and Castillo 2021). A recent report shows that labor costs in specialty crop operations went up 50.8% between 2007 and 2021 (Hall 2021). Plant protection products and fertilizers also became more costly to growers, with increases ranging from 15.8% and 17.1% in the past 15 years. When agricultural inputs for specialty crop operations are examined in aggregate, industry reports indicate that prices paid by growers increased 41.5% between 2007 and 2021. In the short term, aggregate input costs increased by 10.1% (2021 vs. 2020), and the expectation was for an 8% annual increase in 2022 (Hall 2022).

In addition to the challenges imposed by labor and input costs, inconsistent weather patterns and pressure from biotic stressors add new layers of complexity to commercial vineyards across the midwestern United States. Therefore, a rigorous feasibility analysis for investing in field mechanization to assist growers in managing operational costs and uncertainties has never been more critical.

Fortunately, agricultural engineers and plant scientists have developed and validated new ways to assist wine-grape growers with production tasks. Most vineyard operations today (i.e., fertilizer application, hilling and dehilling, pruning, shoot positioning, trimming, suckering, cluster thinning, harvesting, lawn mowing, weed control, and spraying) have mechanization alternatives in place. Among these operations, pre-pruning, trimming, and harvesting have the highest levels of mechanization adoption. Dokoozlian (2013) estimated that trimming is the most common mechanized operation among California wine-grape producers, followed by harvesting and pre-pruning.

The recently developed intelligent spraying technology (Shen et al. 2017; Zhu et al. 2017) may represent a fourth type of mechanization available to improve the efficiency of vineyard operations. Intelligent sprayers use a light detection and ranging laser sensor to measure canopy architecture and density while simultaneously accounting for tractor speed to make plant-targeted spray applications using pulse width-modulated solenoid valves (Shen et al. 2017; Zhu et al. 2017). Intelligent sprayer technology can be retrofitted to existing axial airblast sprayers as well as quantum mist sprayers or pneumatic shears sprayers (Smart Guided Systems LLC, Indianapolis, IN, USA). Both new and retrofitted intelligent sprayers have the ability to reduce input use while enhancing operational efficiency and maintaining the yield and quality of harvested wine-grape clusters (Manandhar et al. 2020; Nackley et al. 2020; Wodzicki et al. 2020).

Nevertheless, a critical question that remains to be addressed is how intelligent sprayers compare with pre-pruners, mechanized trimmers, and self-propelled harvesters from an economic cost–benefit standpoint. A comparative feasibility analysis is to quantify the economic impact of alternative mechanization strategies in a range of production scenarios and scales. This study aims at closing the scientific gap while offering practical results to practitioners and stakeholders interested in reducing the operations’ exposure to increasing input costs and labor shortages.

This study complements the literature on comparative feasibility analysis of vineyard mechanization strategies. An excellent resource is Morris (2007).
Through a cooperative partnership between University of Arkansas and two for-profit companies, the author shows that mechanization of vineyards reduces operational costs by 62% and 45% compared with hand-farmed wine grapes. Cost reduction results were obtained while maintaining crop yield, fruit quality, and sales of the resulting wine. The study evaluated the effects of mechanized pruning, shoot thinning, and fruit thinning on six cultivars commercially grown in Santa Margarita, CA, USA.

This article evaluates how a recently validated spraying technology compares with widely accepted mechanization strategies such as pre-pruners, trimmers, and self-propelled harvesters. We do so by integrating field results from experiments where plant pathologists measured pest and disease control efficiency of intelligent sprayers into a comparative financial feasibility analysis of investing in vineyard mechanization. In addition, we use current prices for ag-inputs and the mechanized equipment evaluated.

**Materials and methods**

This article departs from a production budget for wine-grape vineyards in midwestern United States and examines the effect of introducing mechanization on total costs and economic feasibility metrics. It takes a cost–benefit analysis approach to factor in alternative investments in mechanization and the likely reductions in labor and input costs. The data associated with the adoption and use of pre-pruners, mechanized trimmers, and self-propelled harvesters come from the previous effort of preparing an enterprise budget (Signorini et al. 2022), whereas intelligent sprayer data comes from a recently completed plant pathology study conducted at The Ohio State University (Wodzicki 2022). The study aimed to compare the control efficiency of Japanese beetle (*Popillia japonica*) and foliar diseases during the 2019, 2020, and 2021 production seasons using intelligent sprayer technology vs. conventional airblast sprayer technology. Results show that the intelligent sprayer reduces the volume of chemicals applied to the vines by an average of 54% over 3 years, depending on the vine’s phenological stage and the intelligent sprayer’s flow rate without compromising pest and disease control efficacy compared with the conventional airblast sprayer. This level of reduction in pesticide use is comparable to reductions reported in wine grapes and other small fruit crops, such as highbush blueberry (*Vaccinium corymbosum*) and black raspberry (*Rubus occidentalis*), and several tree fruit crops (Boatwright et al. 2020; Chen et al. 2020; Fessler et al. 2020; Nackley et al. 2020).

We incorporate this input reduction usage factor for intelligent sprayers into a comparative feasibility analysis. The impact of alternative investments on total costs (variable + fixed) and feasibility metrics is organized into seven scenarios: 1) basic mechanization; 2) investment in a pre-pruner; 3) investment in a mechanized trimmer; 4) investment in a self-propelled harvester; 5) investment in a new intelligent sprayer; 6) investment in a retrofitting intelligent sprayer; and 7) investment in a pre-pruner, a trimmer, a harvester, and a new intelligent sprayer (Table 1).

Scenario 1 serves as a baseline for the following six scenarios with investments in mechanization. It considers a $214,859 investment in machinery, including two vineyard tractors, one rough-terrain vehicle (RTV) for field management, one zero-turn lawnmower, one tractor-mounted fertilizer spreader, one tiller, one posthole auger, one post driver, one plow, one grape hoe, one tractor mounting mower, one grass trimmer, one axial airblast sprayer for pesticide applications, a second sprayer for herbicide applications, one water tank trailer, one wagon trailer, and one collar leaf remover. Lawn mowing, plant protection spraying, and leaf removal are modeled as mechanized operations using the preceding equipment, whereas other important operations such as pruning, trimming, and harvesting are modeled as manual operations in the baseline scenario. We estimate an annual average of 87 h/acre labor for all operations, where two wage levels were considered. Skilled and unskilled workers were modeled to receive wages of $18.34 and $15.01 per hour, respectively. We relied on the US Bureau of Labor Statistics (2022) for wages in the Occupational Employment and Wage Statistics report.

The following six scenarios model the introduction of one or multiple pieces of mechanized equipment and evaluate results around four financial metrics. We collected pricing data for a tractor-mounted single-row pre-pruner, a tractor-mounted single sickle bar trimmer, and a self-propelled harvester through a structured phone interview with sales representatives of equipment suppliers that serve vineyards nationwide. The financial metrics evaluated are 1) net present value (NPV) computed at 6% annual discount rate, 2) internal rate of return (IRR), 3) payback also computed at 6% discount rate, and 4) return on investment (ROI). The NPV metric demonstrates the net economic value of an investment over the entire lifespan of the project. Investment projects are financially feasible when NPV is equal to or greater than zero. The IRR expresses the discount rate at which the NPV of a project breaks even. The greater the IRR, the more attractive a given investment is. Payback refers to the amount of time necessary to recover an investment at a predefined discount rate. Investors may prefer projects with low payback time. Finally, the ROI metric summarizes the “bang-for-the-buck” and is the ratio between NPV and total investment in machinery. Investments with large ROI are preferable to projects with low ROI. The computations of NPV, payback, and ROI assume an annual discount factor of 6% because it reflects a representative cost of capital rate and suggests that the hypothetical investments analyzed here take more risk than the lowest US Department of the Treasury bill.

We also depart from a set of background assumptions, either supported by referenced studies or findings from the grapes production budget (Signorini et al. 2022). Hypothetical investments are made in wine-grape vineyards of varying sizes: 30, 50, and 70 acres. For the purpose of this study, we define wine-grape vineyards as production fields planted with one or more cultivars of wine grapes. The vines are cane pruned with shoots trained upward in a vertical position and spaced 8.5 ft between rows and 6 ft between vines. Other cultural management practices are assumed to follow the Midwest Grape Production Guide (Dami et al. 2005). Investments are assumed to be made in year 1 when the vineyard is planted. The vineyard is assumed to remain productive for 23 years, following 3 years for site preparation, trellis construction, planting, and training young vines. The initial 3 years also allow time for the vines to mature and enter production. In total, we examine how hypothetical investments...
Table 1. Summary of results for the cost–benefit analysis, considering a 50-acre (20.2 ha) ‘Cabernet Franc’ wine-grape vineyard.

<table>
<thead>
<tr>
<th>50-acre operation</th>
<th>Investment in machinery and equipment ($/acre)</th>
<th>Total annual cost in years 4–26 (i/acre)</th>
<th>Financial metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Baseline: basic mech</td>
<td>214,859 2,658</td>
<td>13,453 13.2 12.7 3.13</td>
<td></td>
</tr>
<tr>
<td>2) Pre-pruner</td>
<td>+24,000 +480</td>
<td>13,981 13.1 12.5 2.93</td>
<td></td>
</tr>
<tr>
<td>3) Mechanized trimmer</td>
<td>+10,000 +200</td>
<td>15,173 13.9 12 3.37</td>
<td></td>
</tr>
<tr>
<td>4) Self-propelled harvester</td>
<td>+255,000 +5100</td>
<td>13,004 12 13.5 1.38</td>
<td></td>
</tr>
<tr>
<td>5) New intelligent sprayer</td>
<td>+70,000 +1400</td>
<td>15,445 13.7 12 2.71</td>
<td></td>
</tr>
<tr>
<td>6) Retrofitted intelligent sprayer</td>
<td>+36,000 +720</td>
<td>15,940 14 11.8 3.18</td>
<td></td>
</tr>
<tr>
<td>7) All equipment</td>
<td>+359,000 +7180</td>
<td>17,245 13.2 12.1 1.50</td>
<td></td>
</tr>
</tbody>
</table>

1 $/acre = $2.47/ha.
2 Total cost includes operational costs (trellis maintenance, soil/tissue analysis, lime/fertilizer applications, weed control, disease/pest control, canopy management, bird/mammal control, and harvest) and fixed costs (depreciation, opportunity cost of land, and machinery insurance).
NPV = net present value; IRR = internal rate of return; ROI = return on investment; mech = mechanization.

organized into seven scenarios perform in a 26-year project.

We also assume that the baseline scenario maintains the same level of sales that would result from mechanized operations. In other words, the yield and quality of harvested wine grapes are considered to remain the same regardless of the scenario under analysis. This assumption is plausible because the mechanization strategies we evaluate are geared to enhancing operational efficiency and reducing input or labor requirements instead of improving production or fruit quality. This assumption corroborates with Morris (2007) and Wodzicki (2022), in which fruit quantity and quality were unaffected by the introduction of mechanization.

Finally, we do not model risk associated with extreme weather events or wine-grape price fluctuations. Although we recognize that weather and price parameters are critical for examining the feasibility of vineyards, they are external to the analysis of interest. Our primary focus is on the comparative assessment of alternative technology investments, and we use three vineyard sizes to support cost comparisons.

The next section of the article presents simulation results for four investment metrics in every scenario analyzed for a 50-acre operation. Scenario results are put in perspective thereafter and compared across the three proposed scales. We include results for a 30-acre and a 70-acre operation size in Table 2 to broaden comprehension and illustrate the impact of mechanization strategies in real-world applications. Investors and decision-makers are invited to evaluate the four metrics jointly. While positive NPVs indicate financial feasibility at a 6% discount factor, certain investments may require too much upfront capital and compromise the ROI necessary to maintain healthy annual cash flows. Prices and costs are reported in US dollars. Final remarks are offered in the conclusions section.

Results

Scenario 1—Basic mechanization (baseline for scenarios 2–7). The baseline machinery accounts for an annualized depreciation of $234/acre, considering a 26-year investment project. Our model returns a total annual cost of $2658/acre during fully productive years of the vineyard, years 4 through 26 (Table 1). The NPV at 6% discount rate is $13,453/acre, IRR is 13.2%, and payback at 6% discount rate occurs after 12.7 years. The computation of ROI suggests that for every $1 invested in machinery and equipment, the grower may expect $3.13 in return. As one would expect, the feasibility metrics improve with scale gains (Table 2).

Scenario 2—Investment in a pre-pruner. The acquisition of a $24,000 new tractor-mounted single-row pre-pruner is considered in this scenario. Total annual cost decreases by $93/acre during the productive years of the vineyard. Labor requirement is estimated to reduce by 8.3% when compared with the baseline, leading to ~80 h/acre of labor to accomplish all vineyard operations. NPV at a 6% discount rate becomes $13,981/acre, representing an increase of $528/acre compared with the baseline. The IRR is 13.1% and payback occurs after 12.5 years, evidencing improvement relative to scenario 1. The moderate improvement in NPV nevertheless weakens the ROI when we factor in the additional investment. The model suggests that ROI becomes $2.93 per $1
Table 2. Comparison of financial metric estimates for 30-, 50-, and 70-acre (12.1, 20.2, and 28.3 ha) ‘Cabernet Franc’ wine-grape vineyards.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>NPV ($/acre)</th>
<th>IRR (%)</th>
<th>Payback (years)</th>
<th>ROI ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 acres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Baseline</td>
<td>10,189</td>
<td>11.0</td>
<td>14.85</td>
<td>1.42</td>
</tr>
<tr>
<td>2) Pre-pruner</td>
<td>10,270</td>
<td>10.9</td>
<td>14.95</td>
<td>1.29</td>
</tr>
<tr>
<td>3) Mechanized trimmer</td>
<td>11,723</td>
<td>11.6</td>
<td>14.06</td>
<td>1.56</td>
</tr>
<tr>
<td>4) Self-propelled harvester</td>
<td>6,468</td>
<td>8.6</td>
<td>18.26</td>
<td>0.41</td>
</tr>
<tr>
<td>5) New intelligent sprayer</td>
<td>11,181</td>
<td>11.0</td>
<td>14.62</td>
<td>1.18</td>
</tr>
<tr>
<td>6) Retrofitted intelligent sprayer</td>
<td>12,006</td>
<td>11.5</td>
<td>14.07</td>
<td>1.44</td>
</tr>
<tr>
<td>7) All equipment</td>
<td>9,074</td>
<td>9.2</td>
<td>16.89</td>
<td>0.47</td>
</tr>
<tr>
<td>50 acres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Baseline</td>
<td>13,453</td>
<td>13.2</td>
<td>12.67</td>
<td>3.13</td>
</tr>
<tr>
<td>2) Pre-pruner</td>
<td>13,981</td>
<td>13.1</td>
<td>12.53</td>
<td>2.93</td>
</tr>
<tr>
<td>3) Mechanized trimmer</td>
<td>15,173</td>
<td>13.9</td>
<td>11.96</td>
<td>3.37</td>
</tr>
<tr>
<td>4) Self-propelled harvester</td>
<td>13,004</td>
<td>12.0</td>
<td>13.55</td>
<td>1.38</td>
</tr>
<tr>
<td>5) New intelligent sprayer</td>
<td>15,446</td>
<td>13.7</td>
<td>12.03</td>
<td>2.71</td>
</tr>
<tr>
<td>6) Retrofitted intelligent sprayer</td>
<td>15,940</td>
<td>14.0</td>
<td>11.76</td>
<td>3.18</td>
</tr>
<tr>
<td>7) All equipment</td>
<td>17,245</td>
<td>13.2</td>
<td>12.12</td>
<td>1.50</td>
</tr>
<tr>
<td>70 acres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Baseline</td>
<td>14,852</td>
<td>14.2</td>
<td>11.84</td>
<td>4.84</td>
</tr>
<tr>
<td>2) Pre-pruner</td>
<td>15,571</td>
<td>14.4</td>
<td>11.62</td>
<td>4.56</td>
</tr>
<tr>
<td>3) Mechanized trimmer</td>
<td>16,652</td>
<td>15.0</td>
<td>11.16</td>
<td>5.18</td>
</tr>
<tr>
<td>4) Self-propelled harvester</td>
<td>15,806</td>
<td>13.8</td>
<td>11.95</td>
<td>2.35</td>
</tr>
<tr>
<td>5) New intelligent sprayer</td>
<td>17,273</td>
<td>14.9</td>
<td>11.07</td>
<td>4.24</td>
</tr>
<tr>
<td>6) Retrofitted intelligent sprayer</td>
<td>17,627</td>
<td>15.2</td>
<td>10.89</td>
<td>4.92</td>
</tr>
<tr>
<td>7) All equipment</td>
<td>20,747</td>
<td>15.3</td>
<td>10.52</td>
<td>2.53</td>
</tr>
</tbody>
</table>

NPV = net present value; IRR = internal rate of return; ROI = return on investment; $1/acre = $2.4711/ha.
invested in machinery, 6.5% lower than the baseline.

**Scenario 3—Investment in a Mechanized Trimmer.** The acquisition of a new tractor-mounted single sickle bar trimmer worth $10,000 is considered in this scenario. Annual operational costs decrease by $197.83/acre, an improvement of 8.5% vs. the baseline. An expressive total cost reduction of $187.20/acre is primarily pushed by a 13.5% reduction in labor requirements. In this scenario, a total of 75 h/acre is estimated to conduct operations during a productive year of the vineyard. NPV at a 6% discount rate becomes $15,173/acre, representing an increase of $1720/acre compared with the baseline. IRR is 13.9%, and payback occurs after 12 years. Financial metrics show that investing in a mechanized trimmer leads to superior economic results compared with both baseline and scenario 2. The ROI sustains this finding. In this scenario, ROI grows by 7.8% and becomes $3.37 per $1 invested in machinery and equipment.

**Scenario 4—Investment in a Self-Propelled Harvester.** In this scenario, the acquisition of a self-propelled harvester is considered. We simulate the impact of a new $255,000 harvester on operational costs and financial metrics. Due to the sizable investment, the new harvester causes a $212.90/acre increase in annual depreciation. On the positive side, it reduces annual operational costs by 17.9% compared with the baseline, leaving a positive impact of $204.30 in total cost reduction per acre. The cost reduction occurs because harvesting is the most labor-intensive operation in vineyards. Although costly to implement, a mechanized harvesting system reduces exposure to labor shortages. Our estimates indicate that 1 acre requires 62 h/acre of labor when a wine-grape harvester is available, representing a 28.4% cost reduction in annual labor requirements during productive years vs. the baseline. However, the financial metrics suggest a different outcome when the project lifespan is analyzed. NPV at a 6% discount rate becomes $13,004/acre, IRR is 12%, and payback occurs 13.5 years after the investment. Compared with a vineyard with basic mechanization (scenario 1), the investment in a self-propelled harvester causes a $449/acre reduction in the NPV metric. The IRR and payback metrics also demonstrate inferior performance vs. the baseline due to the expensive upfront investment. The estimated ROI is also compromised. In this scenario, ROI falls 55.8% to 1.38, the lowest expected return per dollar invested in machinery across all scenarios analyzed.

**Scenario 5—Investment in a New Intelligent Sprayer.** This scenario uses a $70,000 investment in an intelligent sprayer to examine its impact on economic performance. The simulated investment reduces operational costs by 14.9% or $345/acre vs. the baseline. Although fixed costs increase due to the depreciation of machinery, annualized total costs fall 11%. Unlike other scenarios, the investment in a new intelligent sprayer impacts material and labor costs. Total materials fall by 43.6% and labor costs are reduced by 0.6% due to efficiency gains in refining the sprayer’s tank. The NPV computed at a 6% discount rate increases $1993/acre per year compared with the baseline, reaching a total of $15,446/acre in the 26-year vineyard project. The IRR reaches 13.7%, and payback at a 6% discount rate happens 12 years after the initial investment. Similar to the self-propelled harvester, the expected return on investing in a new intelligent sprayer deteriorates due to a moderate upfront investment. The computed ROI indicates that growers would experience returns of $2.71/acre for every $1 invested, 13.4% lower than the baseline. It is worth noting that we did not model a plausible liquidation of the used sprayer. Considering that the new intelligent sprayer will substitute the existing sprayer in vineyard operations, the used equipment could be sold for a salvage value. In that case, the financial metrics would improve.

**Scenario 6—Investment in a Retrofitted Intelligent Sprayer.** This investment has superior results compared with investment in a new intelligent sprayer. If the commercial grower owns an airlast, a quantum mist, or a pneumatic shear sprayer in good condition, retrofitting it to accommodate the intelligent technology would be an interesting route. In this scenario, an investment of $36,000 is simulated to retrofit a used axial airblast with a face value of $17,000. The impact on variable costs would be the same as for the new intelligent sprayer. Annual depreciation would be lower compared with a new intelligent sprayer because of its purchase value. Simulation results indicate an increase of $51/acre in the annualized depreciation compared with the baseline. The NPV at a 6% discount rate reaches $15,940/acre, which is $2488 on a per-acre basis superior to the baseline. The IRR is 14.0%, and payback occurs 11.8 years after the beginning of the vineyard establishment. The ROI metric shows a 1.5% improvement because the initial investment is lower than buying a new intelligent sprayer. Results indicate present value returns of $3.18 for every $1 invested.

**Scenario 7—Investment in All Equipment.** We finally simulate the impact of a joint investment in a pre-pruner, a mechanized trimmer, a self-propelled harvester, and a new intelligent sprayer. For this to happen, the grower would need an additional $359,000 upfront investment to integrate the initial investment of $214,859 in the baseline. The annualized depreciation cost increases by $337/acre vs. the baseline. However, variable costs offset the negative depreciation impact and lead to a 29.4% total cost reduction, estimated at $773/acre per year. Efficiency gains are obtained due to a 43.6% reduction in material costs and a 50.8% reduction in labor costs. Employing a pre-pruner, a trimmer, a harvester, and a new intelligent sprayer reduces annual labor requirements to 43 h/acre vs. 87 h/acre in the baseline. The cost of running equipment increases by 2.6%.

The financial metrics are as follows: NPV at a 6% discount rate is $17,245/acre, IRR is 13.2%, and payback happens in 12.1 years. Although these metrics show considerable improvement over the other scenarios analyzed, ROI suggests that the steep initial investment does not strengthen present value returns enough. This metric reaches $1.50, the second lowest ROI estimate over all scenarios analyzed. Table 1 summarizes the cost–benefit analysis results for a hypothetical 50-acre operation.

Results maintain consistency when scale variations are introduced. The self-propelled harvester reaches low performance in all three scales analyzed due to its expensive upfront investment. Even though mechanized harvesting cases the most demanding labor operation in vineyards, the simulated cost
reduction is limited and does not perform as well as other investment alternatives. On the other end of the performance spectrum, the mechanized trimmer and the retrofitted intelligent sprayer are superior in every operation scale analyzed. The color range used in Table 2 facilitates this interpretation. Green represents the best estimate for a given metric, and red represents the worst. Intermediary metric estimates take light green, yellow, or orange highlights.

Magnitudes of metrics change considerably as the production scale grows, suggesting that acreage has a direct impact on economic feasibility. Operations that rely on manual labor reach moderate performance in small vineyards and become less effective as scale grows. The metric estimates obtained in the basic mechanization scenario support this argument. The analytical results from scenario 7 indicate that the opposite argument is also valid. Highly mechanized operations reach superior economic performance in large vineyards and lose effectiveness as acreage declines. Table 2 summarizes these results.

**Discussion**

Not all scenarios improved the financial metrics NPV, IRR, and payback compared with the baseline. Small operations (30 acres or less) had mixed results, indicating that production scale may constrain certain types of investments. Pre-pruners, trimmers, and intelligent sprayers lead to positive or neutral impacts on NPV, IRR, and payback because these investments require low upfront investments compared with harvesters or a complete set of equipment, as examined in scenario 7.

As the production scale grows, financial constraints are alleviated. Results show that investing in a full set of mechanized equipment leads to feasibility gains in medium-sized operations (50 acres). Self-propelled harvesters continue to demonstrate limited feasibility as the financial metrics NPV, IRR, and payback worsen compared with the baseline scenario. All scenarios returned improved financial metrics in the 50-acre operation vs. the 30-acre operation.

Large operations face lower barriers to investments in mechanization. Results show that large vineyards (70 acres or more) accommodate investments better than medium and small-scale operations. The financial metrics NPV, IRR, and payback improve significantly over all scenarios analyzed in a 70-acre operation except scenario 4, where a self-propelled harvester was examined. Harvesters show improved NPV estimates, but IRR and payback estimates are lower than the baseline. It is worth noting, however, that commercial vineyards take 10 years or more to payback, regardless of the scale and level of mechanization employed.

The financial metric ROI complements the findings obtained through the analysis of NPV, IRR, and payback. Our estimates show an improvement of ROI for every scenario analyzed as the production scale grows and highlight two types of investments with consistently superior economic performance. The mechanized trimmer and the retrofitted intelligent sprayer in scenarios 3 and 6, respectively, are the only cases with higher ROI in every production scale analyzed. The mechanized trimmer improves ROI of commercial vineyards by a range between 7.1% and 9.9% compared with baseline scenarios in each production scale. The retrofitted intelligent sprayer shows similar results. The improvement of ROI ranges from 0.9% to 1.7% compared with the baseline and conditional on the production scale. The relatively inexpensive upfront investments and their impact on cost savings explain these results. The other four investment scenarios resulted in decreased ROI estimates regardless of the production scale.

These results have direct implications for wine-grape growers and crop consultants. If financial resources are available or can be obtained at low interest rates, investing in all mechanized equipment (scenario 7) seems appropriate for medium- and large-scale operations. Scenario 7 reduces total annual costs by between $773 and $916 per acre per year and increases NPV to the highest levels for medium and large operations. These results nevertheless come at the cost of reducing annualized ROI.

A more plausible and realistic outcome for growers is the consideration of alternative investments to address exposure to input costs or labor shortages. Under these circumstances, the mechanized trimmer and the retrofitted intelligent sprayer are well-balanced investment decisions. They not only improve NPV, IRR, and payback during the 26-year project, but also increase the expected annual ROI, regardless of the operation size. Table 2 illustrates this argument.

Two additional aspects are worth discussing. First, investing in a retrofitted intelligent sprayer may benefit growers to own a suitable type of sprayer in good working condition. In that case, growers will need to purchase the intelligent system and install it in the existing equipment. Our internal research indicates that the intelligent spraying system sells for approximately $36,000. Second, growers may emphasize their primary goal and consider the best equipment to address the operational issue of choice. If the goal is to address challenges associated with labor shortages, investing in a mechanized trimmer may be the most effective investment. Alternatively, if the grower’s objective is to reduce exposure to high pesticide and fertilizer costs, both versions of the intelligent sprayer return superior cash flow performance compared with the baseline. Although the retrofitted sprayer would stand as the most effective investment, a new intelligent sprayer would benefit growers long term by reducing input use and operational costs. However, a $70,000 upfront investment is not appealing to medium-sized vineyard operations in the midwestern United States. A new intelligent sprayer priced at $41,605 would become more attractive to wine-grape growers given that its estimated ROI would equal the baseline while reaching superior cash flow performance as indicated by the NPV, IRR, and payback analyses.

The analytical results presented in this article represent a set of numerous potential combinations of factors and productive assets available to growers. Although we attempted to broaden our simulations to resemble reality as much as possible, commercial growers are likely to experience specific situations and investment opportunities that differ from the scenarios used here. These differences are likely to affect financial metrics estimates. We encourage interested growers to adapt our analytical approach to better represent their reality before evaluating financial performance of alternative investments. The authors are available to facilitate further analysis on request.
Besides the mechanized equipment considered in this study, future research may expand the list of mechanization strategies and examine the economic feasibility of investing in tunnel sprayers that recycle unused pesticides (Ade et al. 2007), autonomous weeding robots (McAllister et al. 2019), or robots programmed to control wine-grape diseases with ultraviolet light (Gadoury 2019). Future studies may also focus on other fruit orchards and examine the economic feasibility of investing in intelligent sprayers vs. conventionally adopted mechanized equipment.

In addition, future research can also compare the equipment in terms of their environmental stewardship. Although previous studies suggest that intelligent sprayers are less prone to cause airborne drift or ground loss due to reduced volume of product mix (Chen et al. 2013; Chen et al. 2020; Fessler et al. 2020; Salcedo et al. 2020; Silva et al. 2018), further research is necessary to quantify the environmental impact of such technologies. Intelligent sprayers must be examined as potential candidates to enrich regenerative agriculture programs led by nonprofit and for-profit organizations and companies. Regenerative agriculture is a set of agricultural practices focused on growing food, fuel, feed, and fiber in harmony with nature, minimizing land degradation and environmental impacts (US Department of Agriculture 2019). Finally, government subsidies for environmental stewardship can be added to the feasibility equation to reduce the burden of expensive upfront investments. A program that can be considered in future studies is the Pesticides Environmental Stewardship Program, managed by the US Environmental Protection Agency (2022).

Conclusions

This article compares the feasibility of seven investment scenarios in mechanization under three production scales. Results show that investing in mechanized trimmers or retrofitted intelligent sprayers improves feasibility in the long run, as shown by NPV, IRR, and payback estimates for medium- and large-scale operations, but also compromises ROI. Finally, the investment in a self-propelled harvester alone demonstrates limited feasibility regardless of the scale.

Intelligent sprayers show attractive cost-reducing potential. By reducing input usage requirements by 54%, both retrofitted and new intelligent sprayers reach positive financial results. The retrofitted intelligent sprayer increases NPV by 18% and ROI by 1.5% in medium-sized operations. The new intelligent sprayer increases NPV by 15% but reduces ROI by 13.4% compared with the baseline. The ROI reduction was studied further, and results indicate that pricing the new sprayer at $41,605 or less would improve wine-grape growers’ willingness to invest. At that price point, ROI would break even with that obtained in the basic mechanization scenario. Both types of intelligent sprayers nevertheless reduce total production costs by 9% or more at any production scale analyzed. Finally, a mechanized trimmer is found to be the most effective investment for managing labor shortages. In addition to reaching positive financial metrics, it reduces labor requirements by 13.5% compared with the baseline. Further research could focus on the environmental stewardship of intelligent sprayers to support the development of facilitated loans or programs.

References cited


