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Evaluating the Economic Viability of Regenerative Viticulture in Sonoma County, California

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Abstract

Background and goals

The transition to regenerative agriculture (RA) is gaining attention for its potential to enhance sustainability in viticulture, but questions remain about its economic feasibility. This study investigates the farm-level economic implications of transitioning to RA in the viticulture sector, with an application to California's North Coast region, specifically Sonoma County.

Methods and key findings

We analyzed data from four vineyards to evaluate the financial outcomes of implementing RA practices (e.g., no-till, composting, and livestock integration) compared to conventional viticulture (CV) practices. Our findings reveal that CV and RA practices result in comparable profitability over a 30-yr time horizon, with RA averaging 5% lower in net present value across vineyards, assuming no change in yields. While in-house RA practices involve higher initial costs, they provide long-term benefits, including lower operational expenses, improved soil health, and additional revenue from sheep grazing integration. The profitability of RA is influenced by site-specific factors such as grape variety, vineyard layout, vine age, and density, as well as by the ability to maintain yields or obtain price premiums that compensate for potential yield reductions.

Conclusions and significance

The results of this study suggest that RA practices can achieve economic outcomes comparable to CV practices over the long term, particularly under the site-specific conditions of Sonoma County. Understanding the financial tradeoffs and benefits of RA can support growers in making informed decisions about transitioning to more sustainable viticulture practices.

Key words: cost-benefit analysis, ecosystem services, operational costs, regenerative agriculture, soil health, viticulture economics

Introduction

The transformation of global agricultural production systems to address climate change and ensure food security requires long-term investment in practices that support ecosystem services (Tilman 1999, Semeraro et al. 2023). Ecosystem services such as soil fertility and biodiversity contribute to carbon sequestration and improve the ability of agriculture to withstand extreme climate conditions (Daba and Dejene 2018, Qiao et al. 2022). However, adopting agricultural practices that support soil fertility, biodiversity, and carbon sequestration is often hindered by improperly aligned incentives and a lack of information.

Regenerative agriculture (RA) presents a holistic approach that seeks to improve environmental, social, and economic health through practices that rejuvenate biodiversity and soil health (Francis et al. 1986). Central to RA is soil health, defined as the soil's continued capacity to function as a living ecosystem that sustains plants, animals, and humans (Lal 2016, Schreefel et al. 2020). RA principles emphasize consistent organic matter contributions, keeping living roots and ground cover, promoting biodiversity, integrating livestock, and minimizing soil disturbance. These strategies aim to reduce reliance on synthetic inputs while improving the soil's ability to store carbon, retain water, and withstand extreme conditions (Khangura et al. 2023). In practice, RA management may involve cover cropping, composting, reduced tillage, and the integration of livestock to crop cultivation.

Herein, we study the farm-level economic impacts of adopting RA practices in the viticulture sector in California's North Coast region, specifically Sonoma County. Grapes are the second most valuable crop in California (CDFA 2023a), a state that is facing a push by state

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policymakers to adopt climate-smart agricultural practices (Medellín-Azuara et al. 2024). RA practices may be particularly suitable for the production of winegrapes because the perennial nature of grapevines allows growers to capitalize on the often long-term benefits of RA. Furthermore, grapes may be especially vulnerable to climate change, as increasingly intense droughts and higher air and soil temperatures pose significant risks to the phenology, yield, and quality of winegrapes (Schultz and Jones 2010, Costa et al. 2016, 2022, Santos et al. 2020). RA practices not only contribute to climate change mitigation but may also offer economic benefits by improving soil health and crop quality over time (Muscas et al. 2017, Peng et al. 2022a, 2022b). While research on the effect of RA practices has primarily focused on crops such as wheat, cabbage, soy, peas, and almonds, these practices also have the potential to affect grape production (Fenster et al. 2021, Montgomery et al. 2022, Musto et al. 2023).

Although limited in comparison to other crops, studies within the viticulture sector have demonstrated that RA practices can improve soil health without compromising yield or industry-defined quality (Lazcano et al. 2022, Brewer et al. 2023). For instance, cover cropping has proven to be beneficial in perennial systems because it helps prevent soil erosion and reduces irrigation needs in changing climates (DeVincentis et al. 2020, Lazcano et al. 2020, Novara et al. 2021). The addition of compost can improve nutrient availability and promote carbon sequestration, leading to healthier soil (Martínez-Blanco et al. 2013, Lazcano et al. 2020), and it also helps to efficiently manage biowaste, lowers transportation costs, and reduces landfill emissions (Mu et al. 2017).

Farmers who have integrated sheep grazing have seen the stimulation of soil carbon flux, an increase in soil carbon storage, and an increase in microbial biomass carbon (Brewer et al. 2023). At the same time, greenhouse gas emissions (including nitrous oxide, methane, and carbon dioxide [CO_2]) remain comparable to those of non-grazed soils (Lazcano et al. 2022). Additionally, the integration of sheep generates potential income through the production of merchantable by-products and decreased input costs (Salinas-Martínez et al. 2022). Farmers who have integrated livestock have reported savings resulting from reduced mowing and herbicide use of 100% and 66%, respectively, relative to conventional management (Niles et al. 2018). However, transitioning to RA involves additional costs and it is not always obvious if, and when, investments will pay off.

Several factors may be preventing the broader adoption of RA among growers. One key challenge is a limited understanding of RA's financial viability, despite growing evidence demonstrating its potential environmental and economic benefits for winegrape growers (Ryschawy et al. 2021). Concerns remain about the effect of RA on winegrape yields and quality, with some studies indicating potential variability in outcomes, depending on site-specific factors and the specific RA practices implemented (Muscas et al. 2017, Zumkeller et al. 2023). Second, RA practices often require several years before the full range of benefits and costs becomes evident (Khangura et al. 2023). The long-term nature of the benefits may not be internalized by growers who are focused on the short term or who have limited capital resources. Finally, many of the benefits are environmental, and thus public in nature, and private growers may not be incentivized to adopt nascent practices for the social good. Our analysis examines these factors through a comprehensive economic assessment of the transition to RA, considering initial investments and the integration of RA practices into existing operations.

This work reports a comprehensive cost-benefit analysis that was conducted at the vineyard level by collecting primary agronomic and financial data from four vineyards in Sonoma County. The aim was to provide insights into RA's practicality and economic viability across diverse winegrape varieties and conditions. We evaluated the financial performance of each medium-sized vineyard under both RA and conventional viticulture (CV) practices and compared the net present value (NPV) of profits under each regime over a 30-yr time horizon. Our analysis tested the hypothesis that RA will affect economic outcomes through reduced input costs and enhanced ecosystem services. We further compared the economic tradeoffs associated with outsourcing compost and livestock as opposed to maintaining them in-house, a choice that needs to be made by those considering the transition to RA. Finally, we used a sensitivity analysis to test how varying assumptions about yield reductions and price premiums influence the economic outcomes of RA adoption.

Materials and Methods

Four vineyards (each owned and operated by a single vineyard and winery company) located in Sonoma County, CA were examined to assess the long-term economic impact of RA compared to CV. RA practices include no-till, cover cropping, compost application, and livestock integration, while CV practices involve alternate tillage, synthetic fertilizers, and herbicides. For the sake of this article and analysis, we refer to the non-RA vineyards as "conventional" but note that the company farms these vineyards in accordance with the certification requirements of the California Sustainable Winegrowing Alliance (CSWA; https://www.californiasustainablewinegrowing.org). Data collection was focused on input costs for vineyard establishment and operating expenses, and revenue projections were based on historical yields and average prices from recent California Grape Crush Reports (CDFA 2023b, 2024). A sensitivity analysis was conducted to assess potential risks related to yield fluctuations and possible market price premiums associated with RA practices.

Vineyards studied and management scenarios

The study was conducted in Sonoma County, one of California's most prominent wine regions, and home to 18 American Viticultural Areas (AVAs) (Harding et al. 2023). By 2021, the county had over 25,091 ha of vineyards, characterized by diverse microclimates and soil types across its AVAs (Harding et al. 2023). Sonoma County has seen a consistent increase in the total value of its winegrape production across red and white varieties, predominantly of Pinot noir and Chardonnay. The production value increased from $149 million in 1992 to $547 million in 2022; the leading winegrape contributors to this value were Pinot noir (valued at $157 million), Chardonnay (valued at $144 million), and Cabernet Sauvignon ($123 million) (SCDA/W&M 2021).

The four vineyards chosen for this study are located in the Russian River Valley and Alexander Valley AVAs (Figure 1) and are part of a broader research initiative with the same company, aimed at investigating the environmental and economic impacts of regenerative viticultural practices. Vineyard site 4, situated in the Russian River Valley AVA, exemplifies the climatological conditions relevant to our study. Over a 10-yr (2013 to 2023) period preceding the study, this location experienced monthly average values of 13.5°C for air temperature, 70.9% for relative humidity, 17.5°C for soil temperature, and 53.8 mm for precipitation, with most rainfall occurring from November to April (California Irrigation Management Information System; https://cimis.water.ca.gov).

Vineyards in the CV scenario employ practices that support soil health in line with CSWA certification requirements. These practices reflect a relatively sustainable form of CV compared to industry-standard "conventional" vineyards that may not follow certification protocols. The CV practices implemented in these vineyards over the five years preceding the study included alternate tillage, which involves tilling the soil in every other alleyway each year, typically in spring (April to May) and late fall (October to November). Alternate tillage, conducted by using a rototiller or disk twice per year at a depth of 10 to 12 cm, primarily is used to incorporate compost and pruning wood, but it also enables a minimized soil disruption, in comparison to tilling all alleyways each year. Immediately following tillage, cover crops such as white clover, annual barley, and rye were established in tilled alleyways in late fall (October to November) at a rate of 67 kg/ha once per year; here, the cover crop was sown in all the rows, both tilled and nontilled. Cover crop mowing was conducted twice per year, typically from April to June. Undervine weed management was performed at a till depth of 2 to 5 cm in early spring (March to April) and again in early summer (June to July),

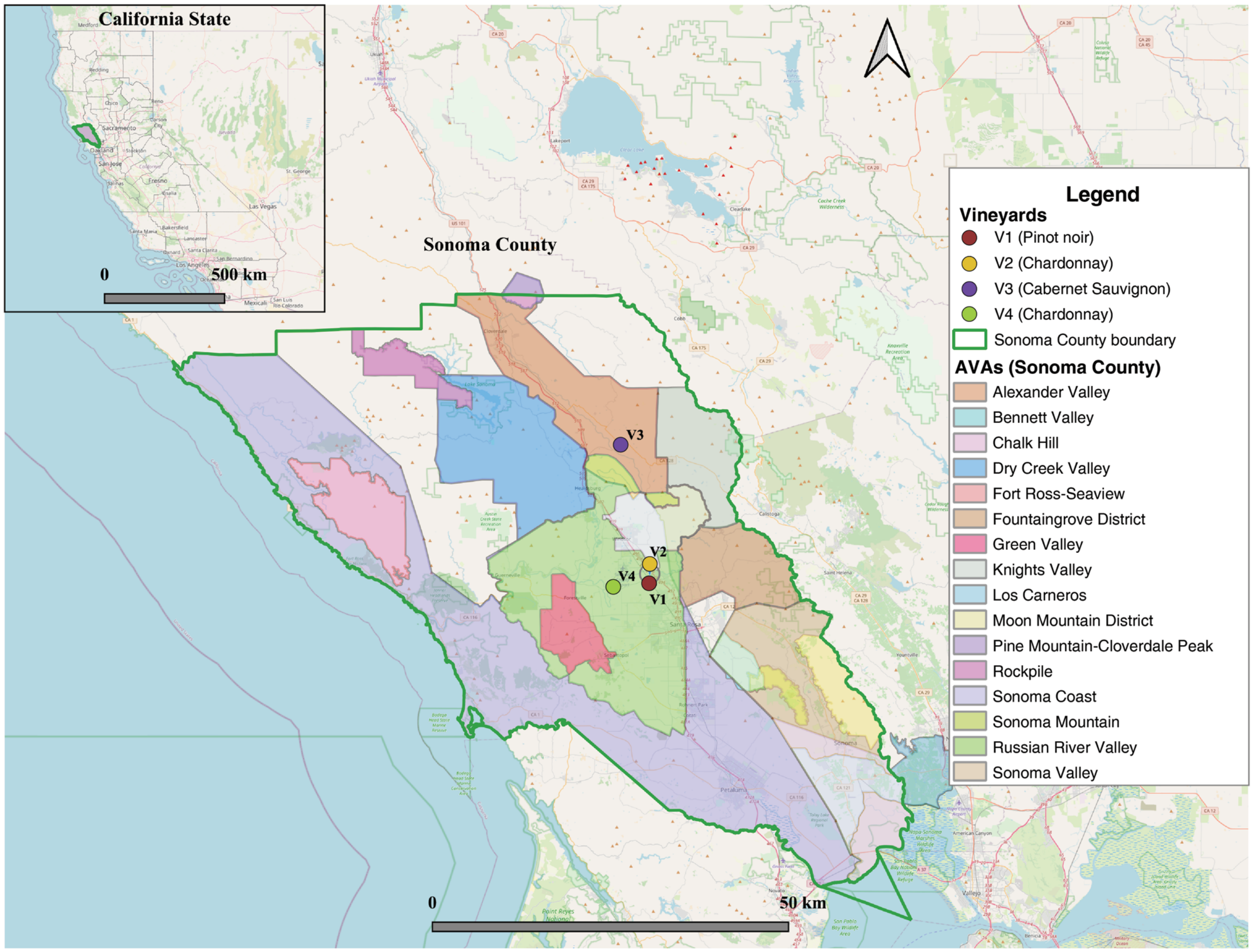


Figure 1 Location of the four vineyards studied and the main American Viticultural Areas (AVAs) in Sonoma County, CA. Map generated using QGIS geographic information system software (ver. 3.36.0-Maidenhead; QGIS Development Team).

and included herbicide application (e.g., Lifeline; at a rate of ~3.7 L/ha, two to three times per year) as well as mechanical control using a Clemens (a side weed knife for undervine management). Vineyard characteristics are presented in Table 1.

The RA scenarios included a no-till approach to soil management and the use of a specific sheep forage seed mix for cover cropping (Table 1). This mix is sown annually using a no-till drill seeder at a rate of 112 kg/ha. Notably, RA scenarios eliminate herbicides for undervine weed control and instead, mechanical methods such as a Clemens or mechanical hoe are used two to three times per year. Such mechanical methods involve shallow undervine tillage (2 to 5 cm depth) and therefore are not considered disruptive to the overall no-till system in the alleyways. Compost application is another critical component of RA practices. Compost is spread once annually, typically postharvest, at a rate of 9.88 Megagrams (Mg)/ha through broadcasting (compost: total nitrogen, 15.2 kg/Mg; phosphorus pentoxide, 7.7 kg/Mg; organic matter, 24.8%; all in wet weight). Sheep grazing is an additional practice within the RA scenarios and is typically conducted twice per year between December and April. Each grazing event lasted ~3 to 5 days, with a flock of 20 Dorper sheep covering a 0.4 ha area (equivalent to a density of 50 sheep/ha). Dorper sheep, aged 2 to 4 yr, were selected because of their low maintenance, relatively small size, and docile temperament, which facilitated management in vineyard settings (Conrad et al. 2022). Each sheep contributes ~2 to 3 kg (5% of their body weight) of manure daily (Moreno-Caselles et al. 2002, Lazcano et al. 2022). This grazing practice excludes the need for mowing, suggesting cost savings from this RA management approach relative to CV.

Table 1 Main characteristics of the four vineyards studied under conventional viticulture (CV) and regenerative agriculture (RA) management. Soil type taxonomies were taken from the USDA-NRCS Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/app/). Yield was averaged from 2 yr (2022 to 2023) and average yield prices were taken from the 2022 and 2023 California Grape Crush Reports (CDFA 2023b, 2024). Weed control (under-vine mechanical with a Clemens side weed knife) was performed at a 5- to 10-cm till depth, one to three times per year (spring and summer); herbicides were applied two to three times per year. Mowing occurred only in alleyways, during spring (April to May) then during summer (July to August). Synthetic fertilizers were used in the same amount and form as in the CV scenarios. AVA, American Viticultural Area; Mg, Megagram.

Characteristics	**Scenarios**				
	CV1[a]	**CV2**[a]	**CV3**[a]	**CV4**[a]	**RA (1 to 4)**
Grape cultivar	Pinot noir	Chardonnay	Cabernet Sauvignon	Chardonnay	Same[b]
Clone	Dijon 667	FPS04 Martini	337	FPS04 Martini	Same
AVA	Russian River Valley	Russian River Valley	Alexander Valley	Russian River Valley	Same
Soil type	Yolo silt loam[c]	Yolo clay loam[c]	Positas gravelly loam[d]	Yolo sandy loam[e]	Same
Rootstock[f]	101-14	140-R	101-14	5C	Same
Planted area (ha)	2.04	6.13	4.11	13.6	Same
Vine age (years)	11	6	23	34	Same
Vine density (vines/ha)	5382	3588	3076	1122	Same
Yield average (Mg/ha)	11.6	19.3	7.03	9.7	Same
Price average per Mg ($)	3750	2500	3000	2500	Same
Trellis system	Guyot	Guyot	Scott Henry	Quadrilateral cordon	Same
Crop management					
Soil tillage	Alternate (Rototiller)	Alternate (Disk)	Alternate (Disk)	Alternate (Disk)	No-till
Weed control	Herbicides and mechanical control	Herbicides and mechanical control	Herbicides only	Herbicides and mechanical control	Mechanical control only
Mowing	Twice/year	Twice/year	Twice/year	Twice/year	No mowing
Nutrient management	Synthetic fertilizers	Synthetic fertilizers	Synthetic fertilizers	Synthetic fertilizers	Compost and fertilizers[g]
Cover cropping[h]	Forage mix	Forage mix	Forage mix	Forage mix	Sheep forage mix
Livestock integration	None	None	None	None	Sheep grazing (two events/year)

[a] CV, vineyards employing practices that support soil health, in line with certification requirements of the California Sustainable Winegrowing Alliance.

[b] Indicates the same characteristic across respective site numbers (e.g., Pinot noir for both CV1 and RA1, Chardonnay for both CV2 and RA2, etc.).

[c] Fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents.

[d] Fine, montmorillonitic, thermic Mollic Palexeralfs.

[e] Fine-loamy, mixed, thermic Fluventic Haploxerolls.

[f] *Vitis* parentage by rootstock: 101-14 (*Vitis riparia* × *Vitis rupestris*), 140-R (*Vitis berlandieri* × *V. rupestris*), and 5C (*V. berlandieri* × *V. riparia*).

[g] Synthetic fertilizers were used in the same amount and form as in the conventional scenarios.

[h] Forage seed mix: generally white clover, annual barley, and rye, applied at a rate of 67 kg/ha; sheep forage seed mix: 1% Campeda Subclover, 2% Hykon Rose Clover, 2% Dwarf Essex Rape, 23% Austrian Winter Peas, 35% Winter Ryegrain, and 35% Triticale, all applied at a rate of 112 kg/ha.

Data collection and inventory

The primary data include average values for inputs, outputs, and prices provided by vineyard managers, representing the resources required to establish a new vineyard and sustain annual operations. To collect these data, we developed a structured questionnaire with over 50 quantitative questions (Appendix 1) and conducted in-person interviews with three vineyard managers from a single vineyard and winery company in 2023. The questionnaire was distributed to vineyard managers prior to the in-person interviews so that the managers would have time to prepare their responses. Given that the collected information pertained to anonymous or publicly available data, our study was granted an exemption by the Institutional Review Board (IRB exemption 2126535-1), negating the need for further IRB oversight.

Data collected from the interviews were compiled in an Excel database and converted to the International System of Units. For instance, all initial data was compiled in acres (0.4 ha) and scaled linearly to hectares. Yield values, initially provided as tons per acre, were converted to Mg/ha to ensure consistency across all economic calculations. Some recorded data, mainly related to vineyard establishment, were reported as ranges. In cases of missing data, values from the University of California, Davis Department of Agricultural and Resource Economics (Smith et al. 2017, Zhuang et al. 2019, Murdock and Sumner 2021) were used to supplement the data set, primarily covering indirect costs. These values were largely consistent across years and were cross-validated using the company's internal records.

Values collected directly from vineyard manager interviews are presented (Table 2 and Supplemental Table 1). However, vineyard managers did not report or systematically track several additional benefits associated with regenerative practices, such as the nutrient value of compost, avoided disposal costs of winery waste, reductions in herbicide and mowing costs, or potential carbon credits. Such indirect benefits were estimated from published literature (DeVincentis et al. 2020, Coker et al. 2022, Oliveira et al. 2022) and, where possible, validated using internal company data. While not captured in interview

Table 2 Summary of the monetized cost and revenue components considered in the study for the four vineyards. Details and explanations of the value sources are presented in Appendix 2.

Costs	Monetary value per ha ($)		Years of occurrence
	Low	High	
Vineyard establishment			
Land[a]	100,000.00	150,000.00	1
Soil preparation	1000.00	2000.00	1
Herbicides	300.00	600.00	1
Fertilizers	6000.00	10,000.00	1
Vine planting	7853.00	32,291.68	1
Irrigation system	10,000.00	50,000.00	1
Trellis system	26,984.75	45,509.75	1
Equipment	200,000.00	400,000.00	1
Vineyard operation			
Herbicides	0.00	300.00	2 to 30
Mowing	0.00	380.00	2 to 30
Tilling	0.00	400.00	2 to 30
Fertilizers	450.00	1000.00	2 to 30
Undervine management	200.00	370.00	2 to 30
Pesticides	600.00	1500.00	2 to 30
Irrigation	500.00	1000.00	2 to 30
General labor	11,856.00	23,712.00	2 to 30
Compost purchased with delivery	1000.00	1500.00	2 to 30
Sheep grazing (two events per year)	400.00	500.00	2 to 30
Cover crop seed and planting	40.00	300.00	1 to 30
Property taxes	800.00	1400.00	1 to 30
Insurance	600.00	1000.00	1 to 30
Sanitation services	197.60	300.00	1 to 30
Investment repairs	450.00	2500.00	1 to 30
Offices expenses	370.50	500.00	1 to 30
Capital recovery cost	2000.00	4000.00	1 to 30
Revenue			
Winegrape production	22,600.00	72,375.00	3 to 30

[a] Land purchase costs are based on minimum values and trends for plantable land in Sonoma County (Combs et al. 2022).

responses, these benefits were incorporated into the NPV analysis to distinguish them from direct data reported by growers.

Model construction and assumptions on RA use in vineyards

Our modeling framework follows standard farm accounting principles adapted from the American Agricultural Economics Association (Eidman et al. 1998). More than 50 variables related to vineyard establishment and operations were compiled (Supplemental Table 1), grouped into 32 subcategories (Table 2), and compared across CV and RA scenarios. These variables were assigned a low and high value based on the range covered by the four vineyards, which was influenced by vine type, planting density, and crop operational demands. The years of occurrence of these costs and revenues (either during establishment or throughout annual operations) were determined by using data from interviews and UC Davis economic studies (Smith et al. 2017, Zhuang et al. 2019, Kurtural et al. 2020, Murdock and Sumner 2021). Monetary values for each input were incorporated into the model, based on the year of occurrence for that cost or revenue component.

The model included initial capital expenditures (CAPEX) and operating expenses (OPEX) that were incurred for CV and RA management scenarios since their establishment. First-year costs in both scenarios were differentiated by the non-acquisition of equipment (e.g., no mower and disk tool in the RA scenarios). For the necessary equipment to establish and operate the vineyard, we included annual depreciation, average value, insurance, and maintenance, assuming the machinery serves at least 4 ha over the entire time horizon considered in our study, aligning with typical vineyard operations (Jackson 2020). Equipment costs were amortized over 30 yr. Operational costs for contracting RA services, such as compost acquisition and sheep grazing, were included annually.

Indirect costs related to taxes, interest, repairs, and insurance were primarily sourced from UC Davis economic studies (Smith et al. 2017, Zhuang et al. 2019, Murdock and Sumner 2021). These costs are generally estimated as fixed percentages of asset or land value and show consistency across studies. We used 2021 values when available and supplemented these with values from 2019 or 2017 only if they were not reported in 2021. Investment in maintenance and repairs of equipment were projected at 2% of their average value, with vines and trellis systems both at 0.5%. The potential for damage to trellises or vines by sheep in RA scenarios was acknowledged, although it was considered minimal and variable and dependent on sheep integration experience and vineyard architecture (vine density and growth, and height of the trellis). For instance, the first year was more susceptible to damage because of a lack of experience; therefore, a range for investment in repair was estimated to be between 0.5% and 0.1% of the value of the trellis system and vines for the first and second years of sheep integration. More detailed information on how these costs were estimated is presented in Appendix 2.

In the model, vineyard yields were assumed to reach maturity by the fourth growing season. Labor costs were expected to increase incrementally, starting at 20% in the first year and rising to 50% and 75% in the second and third years of the total production, respectively (as based on the Virginia Cooperative Extension Vineyard Financial Calculator; https://www.pubs.ext.vt.edu/content/pubs_ext_vt_edu/en/AREC/AREC-188/AREC-188.html). This calculation was based on a basic hourly wage of $19 for canopy management hand labor and $22 for machine operators. A productive vine lifespan of 30 yr was assumed, reflecting the typical period of consistent productivity before decline. This timeframe is supported by studies indicating that while some vineyards may be removed or replanted at 30 yr, or remain productive for up to 50 yr, the average productive life is 25 to 35 yr (Carbone et al. 2019, Harding et al. 2023). After 30 yr, issues such as outdated vine varieties and training systems, plant disease, and reduced productivity and quality commonly arise, making this a reasonable timeframe for economic analysis despite some older vines still producing high-quality grapes (Carbone et al. 2019, Harding et al. 2023).

The direct benefits or avoided costs from compost use were calculated by comparing the nutrient content value to the prices of synthetic fertilizers and by assigning a monetary value to carbon sequestration (Coker et al. 2022). Sheep grazing resulted in 100% savings on mowing and herbicide application compared to the CV scenario (Niles et al. 2018), eliminating these annual costs entirely. The benefits of reduced soil erosion from no-till and permanent cover cropping practices were evaluated using the Revised Universal Soil Loss Equation. Reductions in soil losses potentially reached 1.6 Mg/ha/yr (Biddoccu et al. 2020), using an estimated average value of $30/Mg for topsoil (Robinson et al. 2014, DeVincentis et al. 2020).

The long-term benefits to soil health, such as increased organic matter and biodiversity and improved erosion and flood control, are important yet complex to quantify (Brewer et al. 2022, 2023). These enhancements may lead to healthier crops with better quality and improve resilience to climate change, although evidence is still limited (Montgomery et al. 2022, Qiao et al. 2022). Some studies suggest that the initial adoption of healthy soil practices might reduce yield, at least in the short term (LaCanne and Lundgren 2018). Consequently, we assumed that the long-term benefits to soil health will offset any decrease in yield, leading to a long-term projection of no changes in yield between CV and RA scenarios. Furthermore, indirect benefits such as increased soil carbon sequestration have been noted, with carbon valued at $20/Mg CO_2, based on existing literature (Brewer et al. 2022, Wiltshire and Beckage 2022). More detailed information on benefit calculations can be found in Appendix 2.

Economic evaluation

To provide a comprehensive economic evaluation, the analysis began with a global overview of all costs and revenues associated with vineyard operations, including benefits like carbon storage and the nutrient value derived from the application of compost and from the manure produced by sheep grazing. The economic viability of the management practices was assessed over a 30-yr vineyard lifespan, reflecting the typical period of consistent productivity before decline. We tabulated costs and revenues from each year then calculated the NPV of future cash flows (Equation 1),

$$\mathrm{NPV} = \sum_{t=1}^{t=T} \frac{R_t}{(1+r)^t} \qquad \text{(Eq. 1)}$$

where t denotes the year when the value is incurred, T represents the fixed time horizon used in the main analysis, R_t denotes net cash flow (revenue - cost) at time t, and r is the discount rate, which reflects the time value of money, i.e., the principle that future earnings are worth less than earnings received today, due to opportunity cost (Eidman et al. 1998). Further details on the input data used to estimate annual costs and revenues are presented (Supplemental Table 1 and Appendix 2).

Following this calculation, we compared the NPV experienced under CV to that of RA. In a second step, the analysis compared vineyard profitability between cases where RA practices (e.g., acquiring a sheep flock or producing compost) were performed in-house, versus the alternative of outsourcing such services. In all calculations, NPVs were calculated using a discount rate of 2.5%, following recent recommendations for long-term projects (Schoenmaker and Schramade 2024, and as found in the White House Circular No. A-4 [https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/11/CircularA-4.pdf]). We also tested the sensitivity of this assumption using a 4% discount rate and a 25-yr time horizon (see Supplemental Tables 2 and 3).

Sensitivity analysis

We conducted a sensitivity analysis to evaluate the stability of our model's results under varying yield and price assumptions. Scenario-based sensitivity analysis is a widely applied method in agricultural economic assessments that is used to capture financial risks and uncertainty (Krause 2014, Davis and Gómez 2020, DeVincentis et al. 2020, Akinyi et al. 2022).

Grape prices were based on the average values reported for District 3 (Sonoma and Marin Counties) in the 2022 and 2023 California Grape Crush Reports (CDFA 2023b, 2024). While direct evidence on how RA practices affect grape prices is lacking, these practices could influence prices through changes in grape quality or market premiums. To capture this uncertainty, we modeled a ±20% price variation around baseline values, a range consistent with other studies (Zhuang et al. 2019, Davis and Gómez 2020). This range also reflects year-to-year fluctuations from weather and market conditions, providing a conservative estimate that may encompass potential RA-related effects.

Yield is another factor that can be affected by RA practices. For example, French vineyards converting to organic management experienced yield reductions of ~23% in the first year and 35% in the second, with recovery to conventional levels by the third year of transition (Merot and Smits 2020). Similarly, a German field trial found that organic and biodynamic systems produced on average 35% lower yields than integrated management over three seasons, mainly due to disease pressure and temporary nutrient and water limitations during conversion (Döring et al. 2015). However, such yield losses are context dependent and disease-related reductions observed in European vineyards are less applicable to California, where major pathogens such as berry moth and downy mildew are not prevalent. Moreover, the RA practices evaluated in this study did not involve shifts in fungicide use that are typical of organic conversion. Reflecting this evidence and our own early field trial (data not shown), we assumed a maximum yield reduction of 40% relative to the conventional baseline, representing a conservative upper bound during the transition to RA management.

In this analysis, we calculated NPVs for different scenarios and compared them to the baseline NPV. The scenarios ranged from optimistic, offering minor yield declines and higher prices, to pessimistic, showing larger yield reductions and lower prices. The goal was to understand the economic implications of yield reductions and changes in grape selling prices that are associated with RA adoption.

Results

The data collected from four vineyards provided insight into the distribution of both CAPEX and OPEX across categories for CV and RA scenarios. We combined CAPEX and OPEX cost structures with any costs associated with RA practices, as summarized in Table 3. For the CV scenario, CAPEX averaged $236,414/ha, with land acquisition being the largest expense, accounting for 53% of the total initial costs. This was followed by expenditures on equipment (18%), plant materials and planting (15%), trellis systems (5%), and irrigation systems (4%) (Figure 2). Notable high-cost items within the equipment category included tractors, sprayers, hedgers, and pickup trucks, which are used across larger areas typically spanning at least 4 ha. In contrast, the RA scenario showed a similar cost structure for establishment. Still, it was marginally lower (CAPEX: $234,302) because of its reduced reliance on specific machinery such as mowers and tilling implements (disk).

OPEX on the CV scenario averaged $18,098/ha, while in the RA scenario it was slightly higher at $18,404/ha. The primary cost drivers in both scenarios were general labor (56%) and indirect costs (18%) such as property taxes, insurance, maintenance and repairs, and capital recovery costs. This cost distribution aligns with findings from other economic analyses of vineyard operations (Olen and Skinkis 2018, Zhuang et al. 2019). The RA scenario exhibited a comparable cost distribution, with outsourced RA practices accounting for only 8% ($1565) of the total expenditure. On average, annual operating costs under the RA scenarios were $306/ha greater than under CV because additional costs associated with composting and livestock integration outweighed savings related to mowing, tilling, and herbicide use. Among

RA-specific costs, compost acquisition represented the largest share at 57%, followed by sheep grazing (28%) and cover cropping (15%, including seed purchase and sowing).

The primary factors influencing cost differences between RA and CV are presented in Table 3. RA practices required upfront investments such as compost acquisition and application, but offered savings through the elimination of tilling, mowing, and herbicide use. When indirect benefits such as the nutrient value of amendments, erosion control, and potential carbon credits ($386/ha) were considered, these cost reductions helped largely balance RA's higher operating expenses. Compost and manure contributed to fertilizer savings, erosion control reduced soil loss, and carbon credits reflected the sequestration value of RA practices. Incorporating these benefits reduced the average annualized cost difference (calculated on an NPV basis across the 30-yr vineyard lifespan) between RA and CV from $459/ha to $202/ha, indicating that the long-term benefits of RA can help narrow the profitability gap while supporting more sustainable practices.

Economic performance under RA versus CV vineyard management

To evaluate overall financial performance, we combined CAPEX and OPEX cost structures with projected grape revenue and integrated the additional regenerative co-benefits from Table 3. The results of the NPV analysis across all four vineyards (assuming compost and grazing services are outsourced) exhibited a consistent cost structure across sites (Table 4). This uniformity primarily arises from the standardized application of compost, cover cropping strategies, and a single sheep grazing event per year in each vineyard. Similarly, savings from no tilling, no mowing, and eliminating herbicide use were consistent, with minor adjustments based on the type and frequency of weed control methods employed.

Revenue was estimated using average grape prices and assumed identical yields across both RA and CV scenarios. Chardonnay at Site 2 stood out as particularly profitable

Table 3 Parameters influencing cost and benefits per hectare in the outsourced regenerative agriculture (RA) scenario compared to the conventional viticulture (CV) scenario. VM, vineyard manager; Mg, Megagram.

Parameter	Cost ($)	Benefit ($)	Year of occurrence	Description	Source
Mower	-	12,500.00	1	Savings on equipment that are not required when integrating sheep grazing.	VM
Disk implement	-	10,000.00	1	Savings on equipment that are not needed when reducing soil disturbance.	VM
Compost spreader	13,500.00	-	1	One-time investment for equipment to broadcast compost in the vineyard.	VM
Cover crop seed	113.60	-	1 to 30	Cost difference between the forage mix used in the CV scenario and the sheep mix required in the RA scenario.	VM
Compost acquisition	840.00	-	2 to 30	9.88 Mg applied per ha. Costs include trucking. Increases operational costs by 67% of RA-specific costs.	VM
Compost application	50.00	-	2 to 30	Cost associated to broadcasting the compost in the vineyard.	VM
Sheep grazing events	444.60	-	2 to 30	A single sheep grazing event lasts 3 to 5 days by a 20-sheep flock in 0.4 ha. Two events were considered in the year. These events explain the 28% of RA-specific costs.	VM
Nutrient inputs (compost)	-	253.20	2 to 30	Fertilizer nutrient value by considering its N, P, and K nutrient content, and their equivalent from the commodity prices on commercial fertilizers.	Coker et al. 2022, Estimated[a]
Nutrient inputs (manure)	-	18.10	2 to 30	Based on the amount of manure delivered by sheep per day (5% of its body weight), and its fertilizer nutrient value (N, P, K content).	Moreno-Caselles et al. 2002, Ogejo et al. 2010, Marzi et al. 2020, Coker et al. 2022, Estimated[a]
Soil erosion control	-	48.00	2 to 30	Vineyards with permanent cover crop and no-till show average soil reduction losses of 1.8 Mg/ha/yr (74 to 91%).	Robinson et al. 2014, Biddoccu et al. 2020
Carbon credits (compost)	-	64.20	2 to 30	Average carbon sequestration value of compost per Mg, $3.98 to $9.20.	Coker et al. 2022
Carbon credits (manure)	-	2.10	2 to 30	Studies show a 5.3% increase in carbon over 10 yr in topsoil when permanent rotational grazing is adopted. Therefore, an increase of 1049 kg C/ha (5.3%) in 10 yr was estimated.	Wiltshire and Beckage 2022, Estimated[a]
No herbicides	-	170.00	2 to 30	Savings on chemicals and spray costs.	VM
No mowing	-	240.00	2 to 30	Savings on labor and equipment maintenance costs.	VM
No tilling	-	240.00	2 to 30	Saving on labor and equipment maintenance costs.	VM

[a] More information can be found in Appendix 2.

due to higher yields compared to other vineyards (Table 4). Indirect benefits of RA such as carbon sequestration and the nutrient value of amendments provided consistent but minimal cost reductions across vineyards, contributing less than 1% to overall savings. This highlights that profitability in both systems is primarily driven by grape revenue, which depends on site conditions and market pricing.

Across the four vineyards, the results suggest that RA practices yield slightly lower NPVs compared to CV methods. Still, the differences are slight, typically between 1.9% and 8.4%, and may not significantly influence a grower's decision. For Pinot noir (Site 1), RA1's NPV was just 4.6% lower than CV1's, indicating comparable long-term financial performance with added potential environmental

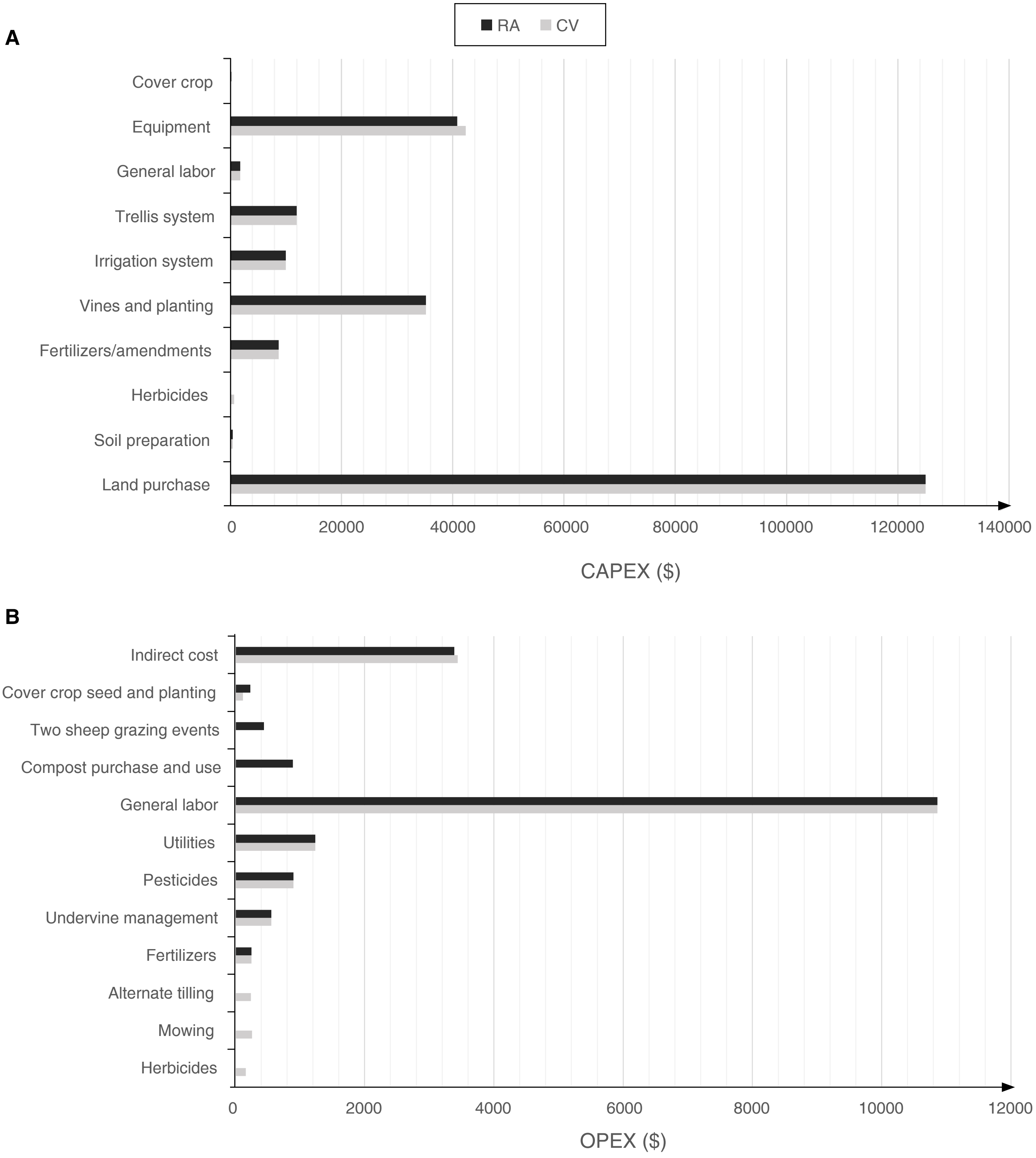


Figure 2 Comparison of cost distribution per hectare along **A**) capital expenditures (CAPEX) and **B**) operating expenses (OPEX) for the conventional viticulture (CV) and regenerative agriculture (RA) management scenarios. "Indirect cost" includes property taxes, insurance, maintenance and repairs, and capital recovery costs.

benefits. For Chardonnay (Site 2), RA2 and CV2 were both profitable, with RA2 posting only a 1.9% lower NPV. In contrast, Cabernet Sauvignon (Site 3) exhibited negative NPVs under both RA3 and CV3, reflecting financial challenges in this scenario; RA3 was 4.9% lower than CV3. Last, Chardonnay (Site 4) showed RA4 at an 8.4% lower NPV than CV4, suggesting a slight financial disadvantage while remaining viable.

The analysis indicates that RA management generally provides financial outcomes that are competitive with CV management, with small differences in NPV percentages across vineyards over the 30-yr evaluation period. We used a 2.5% discount rate for the NPV calculations but also tested the sensitivity of the results with a 4% discount rate. This adjustment did not affect the main conclusions (Supplemental Table 3).

Cost-benefit analysis of in-house RA practices

Important cost differences arise depending on whether certain RA practices—namely, compost and livestock—are developed and maintained in-house or outsourced via purchases or leasing. In-house practices can offer potential long-term savings but require higher initial investments and skilled labor. In contrast, outsourcing reduces initial capital costs, although it may result in higher ongoing operating expenses and dependence on skilled service providers. The following analysis compares these two strategies, focusing on their tradeoffs while holding constant the broader cost differences between RA and CV scenarios.

Composting in-house

On-site compost production leverages waste by-products generated from wine production such as grape pomace, stems, and lees, constituting 27 to 35% of the initial winegrape biomass (Giacobbo et al. 2022). One of the compost formulations tested and adopted by vineyard managers uses 65% wine by-products, 20% manure, 10% wood chips, and 5% landscape waste. Only the manure was purchased externally. Therefore, for a winegrape production of 10 Mg/ha, it is estimated that biowaste by-products from the fermentation process can produce 5 Mg of compost. The compost produced is used as a soil amendment, with an estimated nutrient value (i.e., nitrogen, phosphorus, potassium from 9.8 Mg) of ~$253/ha, which is comparable to typical external fertilizer costs per season (~$250/ha). While this suggests that compost can provide nutrients of monetary value similar to that of synthetic fertilizers, it does not necessarily mean it can fully replace them, as vine nutrient requirements and compost nutrient availability may not align. The in-house production cost of compost is ~$27/Mg (Table 5). This cost is competitive with industrial compost production costs of $16/Mg, reported in the literature (Coker et al. 2022). Compared to the cost of purchasing compost at $70/Mg, producing compost in-house represents ~61% savings.

Livestock integration

Integrating sheep for grazing provides natural weed control, supports nutrient cycling through manure deposition, and enhances soil health while reducing erosion (Niles et al. 2018, Schoof et al. 2021, Brewer et al. 2022, 2023, Ochoa-Hueso et al. 2024). Additionally, producing sheep co-products (such as meat) in-house creates another revenue stream, contributing to the vineyard's overall profitability. Key expenses in sheep production include acquisition (65% of total costs), grazing (15%), utilities and labor (11%), and feed (2.7%) (Salinas-Martínez et al. 2022). In-house grazing significantly reduces feed costs by ~$22 per sheep, boosting net profits by ~$20 per sheep compared to purchasing feed externally (Salinas-Martínez et al. 2022). Maintaining a 10-sheep flock in-house for a 4-ha vineyard incurs annual operating costs of $3500, with potential annual revenue from lamb and mutton sales ranging from $1200 to $1800 (Table 6).

Revenue from Dorper sheep is strongly influenced by breed quality, with high-quality crosses or pure breeds fetching prices up to $6600 per sheep at auctions (https://westerndorper.org/events/past-events/). Dorper ewes have high fertility rates (one to two lambs per year), potentially doubling or tripling flock size annually (Cloete et al. 2000, Milne 2000). They are resilient, disease-resistant, require minimal care, shed naturally (eliminating shearing costs), and produce milder-flavored meat, making them

Table 4 Comparative economic analysis of 1 ha for the conventional (CV) and regenerative (RA) management scenarios in the four vineyards studied over 30 yr. Mg, Megagram; NPV, net present value over 30 yr.

Vineyard (grape)	Density (vines/ha)	Yield (Mg/ha)	Price ($/Mg)	Scenario	Initial investment ($)	Annual operating costs ($)	Annual revenue ($)	NPV[a] ($)	NPV change[b] (%)
Vineyard 1 (Pinot noir)	5382	11.6	3750	CV1	260,043	23,573	43,500	134,372	-4.6
				RA1	257,396	23,908	43,500	128,130	
Vineyard 2 (Chardonnay)	3588	19.3	2500	CV2	250,440	19,370	48,250	312,724	-1.9
				RA2	247,793	19,705	48,250	306,630	
Vineyard 3 (Cabernet Sauvignon)	3076	7.03	3000	CV3	227,659	17,919	21,090	-140,605	-4.9
				RA3	226,148	18,237	21,090	-147,441	
Vineyard 4 (Chardonnay)	1122	9.7	2500	CV4	207,515	11,530	24,250	60,731	-8.4
				RA4	205,874	11,768	24,250	55,622	

[a] Calculation of NPV for RA scenarios assumes composting and sheep flock are outsourced.
[b] Percentage difference in NPV between CV and RA scenarios, calculated as the relative change with CV as the baseline.

economically attractive for meat production (http://www.animalovin.com/dorper-sheep-breed/). Dorper lambs also grow rapidly and attain a high weaning weight, which is economically important in mutton sheep breeding (http://breeds.okstate.edu/sheep/dorper-sheep.html). These traits and their high fertility rates make Dorper sheep an attractive option for maximizing economic benefits for sheep meat production (Byrne et al. 1993, Karki et al. 2018). While in-house practices require more resources, they offer significant long-term financial benefits and support a sustainable integrated business model.

Financial outcomes and long-term viability of in-house RA practices

Financial outcomes combine the indirect benefits of RA (Table 3) with the net annual cash flows generated from sheep grazing and composting (Tables 5 and 6), with results expressed on a per-hectare basis to allow comparison across vineyard scales and with other studies. Over a 30-yr time horizon, discounted at 2.5%, in-house RA management yields a positive NPV of $557/ha, while outsourcing results in a negative NPV of -$1756/ha. On an annual basis, this translates into average net cash flows of ~$19/ha for in-house management and -$59/ha for outsourcing, both relative to the CV baseline (Figure 3).

Both RA approaches benefit from year-1 equipment savings ($2250/ha net) and from indirect benefits that rise from lower values in years 1 and 2 to $1035/ha/yr from year 3, onwards (Table 3). In-house management additionally secures $336/ha/yr in waste-disposal savings through composting, together with $300 to $450/ha/yr in lamb or mutton sales beginning in year 2. These gains are partly offset by composting and sheep operating costs, as well as by periodic capital expenses for compost cover replacement. The result is a cash flow profile that fluctuates over time, reflecting variation in livestock revenues and the 3-yr compost cover cycle.

In contrast, outsourced RA involves constant costs for compost purchase and grazing services but does not capture livestock income or waste-management savings. As a result, its NPV remains negative, despite sharing the same initial equipment savings and long-term indirect benefits (Figure 3).

Sensitivity analysis

We conducted a sensitivity analysis to evaluate the financial impact of potential yield and quality differences under RA management. We estimated the difference in the NPV relative to the conventional baseline, which is calculated in Table 4 across the four vineyards for several scenarios (Table 7). These scenarios ranged from Optimistic (moderate yield decreases and higher grape prices) to Pessimistic (severe yield drops and reduced prices). The NPVs under these scenarios were compared to the CV case (which assumes no yield or price changes) to assess the financial outcomes of transitioning to RA.

Table 5 Costs and benefits of in-house compost production of 20 Megagrams (Mg)/yr for four 4-ha vineyards. VM, vineyard manager; CAPEX, initial capital expenditures.

Category	Cost ($)	Benefit ($)	Year of occurrence	Description	Source
Initial costs					
Turner	8000	-	1	Main equipment required to mix the composting materials. Assuming secondhand equipment.	VM
Utility tractor - front loader	5000	-	1	This assumed tractor from vineyard can be used; only front loader implement would be required.	VM
Thermometers	400	-	1	Four units. Temperature monitoring.	VM
Plastic	80	-	Every 3 yr	Compost pile cover, periodic replacement.	VM
Total initial costs	13,480	-	1		
Annual operating costs					
Labor	1680	-	3 to 30	Management and maintenance of compost (e.g., monitoring, turning, mixing, and adding water): 4 hr once per week for 5 to 6 mo.	VM
Resources[a]	140	-	3 to 30	Mainly water and chicken manure. Additional organic matter if required.	VM
Equipment maintenance	60	-	3 to 30	Tools and machinery.	VM
Total annual operating costs	1880	-	3 to 30		
Annual benefits					
Waste management	-	1344	3 to 30	Savings on waste fee disposal from Zero Waste Sonoma (e.g., yard debris): $112/Mg, and assuming 30% biomass discarded from winegrape.	Zero Waste 2024[b]
Total annual benefits	-	1344	3 to 30		
Net annual cash flow	-	-	-	$1344 - $1880 = -$536/year (Non-CAPEX years)	

[a] Screening to finish size (to achieve homogeneity in compost) was not considered, which can increase cost by up to 40%.
[b] https://zerowastesonoma.gov/disposal-options/central-disposal-site-transfer-stations-fee-schedule.

In Optimistic scenarios, higher grape prices offset moderate yield reductions, resulting in positive NPVs across all vineyards. For example, in the Optimistic scenario (-10% yield, +20% price), NPVs ranged from $24,443 to $65,464, highlighting the financial benefits of improved grape quality. However, losses persisted in the Optimistic I scenario (-20% yield, +20% price), showing that more significant yield declines can negate price benefits.

Moderate scenarios with 5 to 20% yield reductions and small or no price increases showed declining NPVs. For instance, in the Moderate scenario (-20% yield, no price change), NPVs ranged from -$85,031 to -$184,992. Under the Moderate II scenario (-5% yield, +5% price), NPVs ranged from -$5989 to -$8331, indicating that a moderate price increase can help offset a slight decline in yield. In contrast, the two Pessimistic scenarios (significantly lower yields and prices) resulted in negative NPVs in all vineyards.

Discussion

Our findings show that RA can be economically viable, yet profits are ~2 to 8% lower than with CV. This analysis reflects conditions specific to vineyards in the North Coast region, particularly Sonoma County, and results may differ in other grapegrowing regions such as the Central Coast. The economic viability of RA depends largely on keeping stable yields or achieving price premiums to counterbalance any potential yield decline.

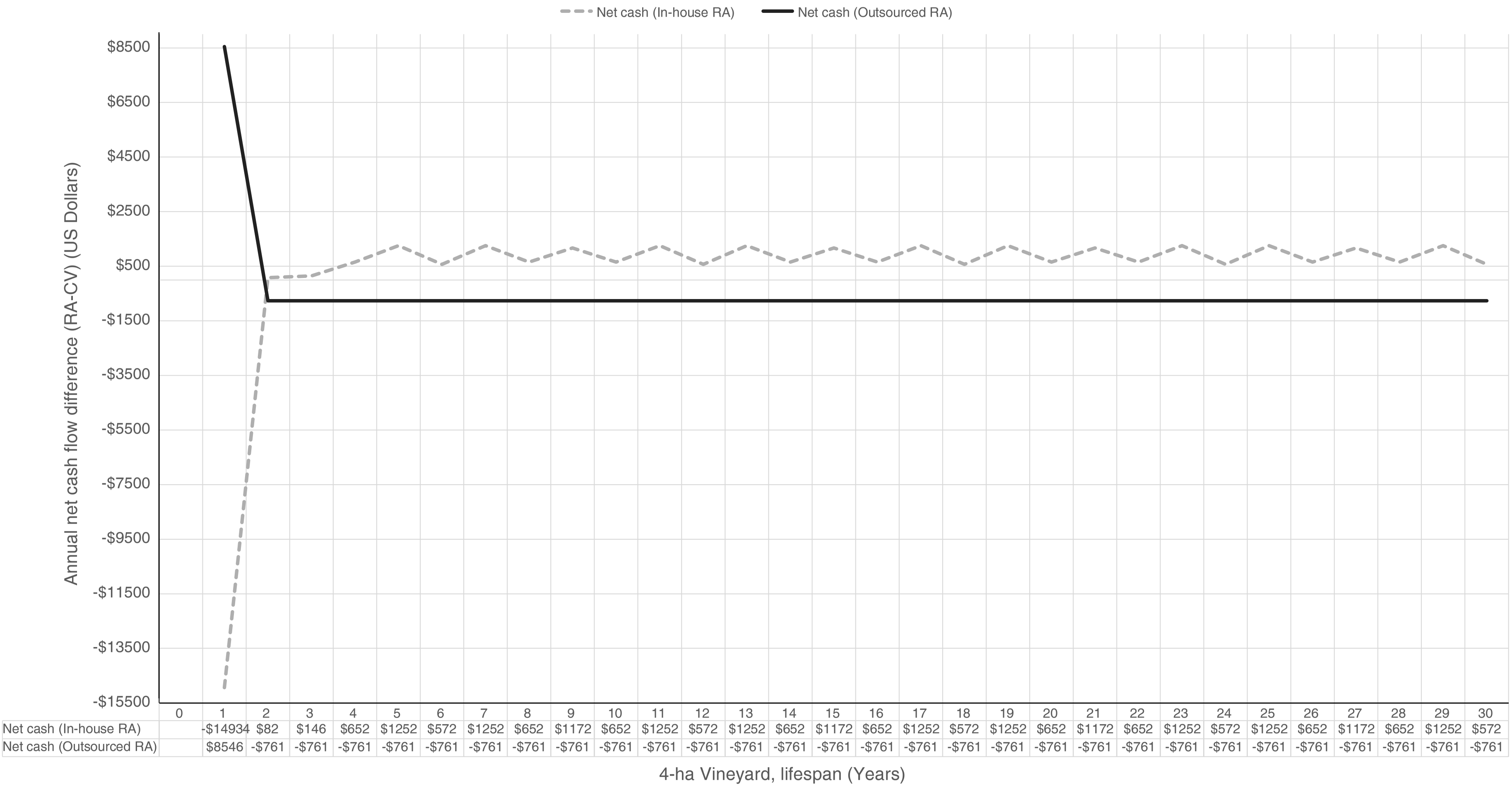
While actual yields from the four vineyards were not included in this analysis, preliminary field-trial observations suggest that RA effects on yield may vary by site-specific conditions, management practices, and grape variety. These observations emphasize the importance of localized assessments when transitioning to RA systems. For instance, factors such as vine density and vine age can strongly influence productivity, particularly during the adaptation and implementation of new management practices.

Table 6 Costs and benefits for in-house sheep grazing integration in a 4-ha vineyard. VM, vineyard manager; CAPEX, initial capital expenditures.

Category	Costs ($)	Benefits ($)	Year of occurrence	Description	Source
Initial costs					
Purchase of Dorper sheep (10-sheep flock)	4000	-	1	Range for commercial crosses are ~$300 to $500 per head. Pure breeds (e.g., South African) can cost ~$2000 to $3000.	VM
Setup costs	6000	-	1	Core infrastructure (fencing, shelter, dog).	VM
Total initial costs[a]	10,000	-	1	Assuming 1 ha would require 2 to 3 sheep to be grazed whole year. Thus, a 10-sheep flock for a 4-ha vineyard was considered.	-
Annual operating costs					
Administrative/management labor[b]	1200	-	2 to 30	Depending on flock size, a herder is needed. A full-time herder can operate a flock of 500 ewes.	Finzel et al. 2022, VM
Fencing and shelter maintenance	100	-	2 to 30	Annual maintenance for fencing, shelter, and watering systems.	VM
Guard dog	1200	-	2 to 30	$100 is the maintenance cost per month for food and medical care.	Finzel et al. 2022
Veterinary and health care	1000	-	2 to 30	Veterinary care includes purchased feed (salts and minerals). Cost is ~$100 per head.	Salinas-Martínez et al. 2022, VM
Total annual operating costs	3500	-	2 to 30	For a 10-sheep flock.	-
Annual benefits					
Income from meat	-	1200 to 1800	2 to 30	At 4 mo, lambs can weigh ~36 to 38 kg. The cost of meat can vary from $4 to $8/kg. Assuming Dorper ewe can lamb three times in 2 yr. An older Dorper is sold as mutton, earning similar per-head prices because of their larger meat quantity.	Salinas-Martínez et al. 2022, Knight and Taylor 2024, VM
Total annual benefits	-	1200 to 1800	2 to 30	Assuming the flock will breed at among 4 to 6 lambs per year, sold at $300 per head.	-
Net annual cash flow	-	-	-	$1200 - $1800 - $3500 = -$2300 to -$1700/yr (Non-CAPEX years).	-

[a] Freight costs are not included because of the small flock size. A small trailer could add ~$5000 to $8000 to the initial cost.

[b] Given the small flock size, herding costs are expected to be minimal. Therefore, no dedicated herder is required and the VM can manage most tasks.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Net cash (In-house RA)		-$14934	$82	$146	$652	$1252	$572	$1252	$652	$1172	$652	$1252	$572	$1252	$652	$1172	$652	$1252	$572	$1252	$652	$1172	$652	$1252	$572	$1252	$652	$1172	$652	$1252	$572
Net cash (Outsourced RA)		$8546	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761	-$761

Figure 3 Annual net cash flows over a 30-yr vineyard lifespan, comparing in-house and outsourced regenerative agriculture (RA) scenarios relative to a conventional viticulture (CV) baseline, expressed for a 4-ha vineyard. Net present value (NPV) was calculated at a 2.5% discount rate. In-house RA produced a positive NPV ($2227 total; $557/ha), while outsourced RA resulted in a negative NPV (-$7024 total; -$1756/ha). In-house benefits include year-1 equipment savings ($9000), indirect benefits rising to $4142/yr, waste-disposal savings ($1344/yr), and lamb/mutton sales ($1200 to $1800/yr), partly offset by composting and sheep operating expenses and periodic compost cover replacement. Cash flow fluctuations reflect variation in lamb sales (four to six animals per year) and the 3-yr compost cover cycle. Outsourced RA shares the same equipment savings and indirect benefits but carries recurring compost purchase and grazing service costs, without revenues from livestock or waste-management savings (see Tables 3, 5, and 6).

Older vines tend to be more vulnerable to disease and may require interventions such as cordon renewal or replanting, both of which can negatively affect yield.

Regarding operational strategies, in-house RA practices show clear economic advantages over outsourcing, given the time horizon we considered. Over 30 yr, our data suggest that in-house RA practices can reach an NPV of $557/ha, while outsourced options show a negative NPV of -$1756/ha. In-house management also cuts transportation costs, which lowers greenhouse gas emissions and potentially qualifies vineyards for carbon credits as an alternative source of income. However, these calculations do not include RA training and experience costs, which often arise when switching to in-house operations. Outsourcing can be more practical for smaller growers because it demands less investment and training, making it a more straightforward approach for starting and gradually transitioning to in-house RA practices.

Although grape quality was not measured in this study, RA practices that promote soil health and vine balance may help create conditions favorable to grape quality over time (Howell 2001, Muscas et al. 2017, Peng et al. 2022a, 2022b). However, grape and wine quality are influenced by many factors such as rootstock, cultivar, planting density, site capacity, and training system, making it difficult to isolate the effect of farming practices alone. While RA practices may contribute to improved vine balance, their direct effect on grape quality remains uncertain without specific measurements. According to our sensitivity analysis, maintaining yields close to those of CV and achieving higher prices for better grape quality is crucial for making RA profitable.

Adopting RA in viticulture presents potential economic and environmental benefits, aligning with the goals of sustainable agricultural transformation. However, it is important to highlight a few key assumptions and limitations of this study that are relevant for broader applicability and interpretation.

External benefits

RA practices provide environmental benefits that extend beyond the vineyard, e.g., via carbon sequestration and enhanced biodiversity. While our study treats carbon sequestration as a private benefit through carbon credits, valuing it at the social cost of carbon (SCC; estimates the public economic damages from CO_2 emissions) reveals a higher overall benefit. For instance, with an SCC estimate of $185/t CO_2 (Rennert et al. 2022), a vineyard annually sequestering 1 t/ha could generate significant long-term value for both the vineyard and society. However, carbon credit markets are not always readily accessible to small operations (e.g., a 4-ha vineyard) because participation often involves administrative and verification costs that can outweigh potential revenue. In our analysis, carbon credits represent a relatively small share of total RA benefits (Table 3). Nonetheless, as SCC is projected to rise, incentives for adopting RA practices could increase considerably.

Furthermore, this study does not consider the valuation of other environmental benefits such as reduced dust and air pollution from no-till practices (Six et al. 2004, Bregaglio et al. 2022), which may affect public health. In vineyards with narrow alleyways and frequent tractor passes (e.g., six to eight sprayer passes and one to two undervine tillage passes per season), undervine cultivation can limit cover crop establishment and increase dust generation. Lower air pollution levels have been linked to reduced healthcare costs and improved quality of life (Landrigan et al. 2018), benefits that are not accounted for in the current analysis. These unvalued benefits suggest that the true economic and environmental impact of RA may be understated, underscoring the need for policy frameworks to recognize and incentivize these external benefits.

Scale of analysis

Although this study focuses on practices at the farm level, environmental impacts from agriculture, such as changes in carbon stocks or greenhouse gas emissions, can extend to regional or global scales (Smith et al. 2017). This broader perspective is important because if RA reduces yields, market responses could increase pressure to expand cropland elsewhere to meet demand, potentially shifting environmental impacts beyond the farm. Such expansion can affect ecosystems negatively (Rockström et al. 2017), offsetting the farm level benefits generated by RA. At the same time, integrating sheep into vineyards can reduce the need for separate pastureland, improve land-use efficiency, and provide additional ecosystem services (Niles et al. 2018, Schoof et al. 2021).

Table 7 Net present value (NPV) comparison for different yield and price scenarios across the four vineyards studied (Optimistic, minor yield declines and higher prices; Pessimistic, larger yield reductions and lower prices). Reported values are the differences in NPV between regenerative agriculture (RA) under each scenario and the conventional viticulture baseline calculated in Table 4. The RA scenario refers to the outsourced implementation. Bold text highlights the only scenario with a positive profit.

Scenario	Yield decrease (%)	Price variation (%)	NPV ($) Vineyard 1: Pinot noir	NPV ($) Vineyard 2: Chardonnay	NPV ($) Vineyard 3: Cabernet Sauvignon	NPV ($) Vineyard 4: Chardonnay
Baseline	0	0	-6242	-6095	-6835	-5109
Optimistic	-10	20	**58,272**	**65,464**	**24,443**	**30,856**
Optimistic I	-20	20	-38,499	-41,874	-22,474	-23,091
Moderate	-20	0	-167,528	-184,992	-85,031	-95,021
Moderate I	-10	5	-50,596	-55,292	-28,339	-29,834
Moderate II	-5	5	-8258	-8331	-7813	-5989
Pessimistic	-30	-10	-304,620	-337,055	-151,497	-171,446
Pessimistic I	-40	-20	-425,585	-471,227	-210,144	-238,880

Nonetheless, farmland biodiversity and the services it provides (e.g., pollination and pest control) often depend on decisions made at various scales, from individual fields to entire landscapes (Grau et al. 2013). Studying RA on a broader scale can provide policymakers with clearer insights for resource management and land-use planning decisions.

Considerations and future research

Transitioning to RA in vineyards requires balancing immediate economic and technical needs with long-term sustainability goals. A critical aspect of this transition involves maintaining key elements of vineyard structure and layout such as vine density, trellis system, rootstock choice, and cover crop species. Depending on the row, vine spacing, and vine training system, sheep integration may or may not be a suitable practice. Rootstock selection should consider soil properties and the competitiveness of the environment for vine growth. For example, rootstocks known for low-to-medium vigor such as 101-14 may not thrive in the biodiverse environment of RA. Alternatively, rootstocks 1103P and 99R may be better suited for RA as they offer higher vigor and yield potential (Ollat et al. 2015, Miele and Rizzon 2017). Similarly, diverse cover crop species can improve ecosystem services including nitrogen fixation, sheep grazing, and attraction of beneficial insects (Smart et al. 2006, de Herralde et al. 2010, Giffard et al. 2022). Nevertheless, other factors like vine age and year-to-year climate fluctuations can influence yield and grape ripeness, regardless of management approach.

Because of these complexities, to ensure success when implementing RA, growers must adapt vineyard management and develop new knowledge and technical skills based on RA principles. Future research should optimize RA for different vineyard conditions by assessing its long-term effect on grape quality and yield, which could help growers make more informed grape pricing decisions. Additionally, developing comprehensive methods that quantify and incorporate the full spectrum of environmental and social benefits into economic assessments will be essential to entirely understand the value of RA practices.

Conclusions

This study demonstrates that RA in viticulture can be an economically viable approach under the site-specific conditions observed in Sonoma County, particularly when grape yields are preserved or price premiums compensate for yield reductions. While outsourced RA services account for a modest portion of operational costs (7 to 8%), in-house RA offers additional benefits, including reduced long-term expenses and increased revenue from integrated practices like sheep grazing. Although RA profits are slightly lower than those from CV practices (-1.9 to -8.4% across vineyards), this difference assumes equal yields between management systems. In-house RA practices can yield higher financial returns (NPV \$557/ha) compared to outsourced options (NPV -\$1756/ha). The economic viability of RA depends on site-specific factors, operational choices, and tailored management practices.

RA can compete with CV but it requires careful management of yield effects and market conditions, along with new policies that recognize and reward the public benefits of these practices. In Optimistic scenarios, price premiums can offset moderate yield reductions, leading to positive NPVs. However, significant yield reductions without corresponding price increases can result in economic losses.

Importantly, this analysis is based on existing vineyards transitioning to RA. For growers establishing new vineyards, there is an opportunity to select rootstocks, irrigation infrastructure, and vineyard design tailored to RA systems, potentially avoiding initial yield losses observed in transitions. This highlights the importance of site-specific planning and intentional design when adopting RA from the outset. Future research should optimize RA practices for different vineyard conditions and quantify RA's long-term economic and ecological impacts at scale.

Acknowledgments

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Supplemental Data

The following supplemental materials are available for this article at [ajevonline.org:](ajevonline.org)

Supplemental Table 1 Main inputs and outputs of initial data collected from interviews on the four vineyards studied. Q, quantity; EV, electric vehicle; UTV, utility terrain vehicle; ATV, all terrain vehicle; Mg, Megagram.

Supplemental Table 2 Economic comparison of different discount rates (DR) and time horizon analysis of 1 ha for the conventional viticulture (CV) and regenerative agriculture (RA) management scenarios. Net present value (NPV) difference = RA - CV. The main analysis uses a 30-yr time horizon (see Equation 1), while this table includes additional time horizons and discount rate combinations to explore sensitivity. Mg, Megagram.

Supplemental Table 3 Net present value (NPV) comparison across yield and price scenarios for four vineyards at a 4% discount rate (DR) and two time horizons (25 and 30 yr). Values represent the NPV difference between regenerative agriculture (RA) under each scenario (Optimistic, minor yield declines and higher prices; Pessimistic, larger yield reductions and lower prices) and the conventional viticulture (CV) baseline from Supplemental Table 2. Bold text highlights the only scenario with a positive profit.

Appendix 1 Economic questionnaire: Cost-benefit analysis in vineyards using regenerative practices.

Appendix 2 More information and sources on how the costs and benefits from the winegrape production systems were estimated.

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Data Availability

The data underlying this study are available on request from the corresponding author.

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