Reducing the Economic Impact of Grapevine Leafroll Disease in California: Identifying Optimal Disease Management Strategies

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Abstract: Grapevine leafroll disease (GLRD) is a devastating viral disease found across all grapegrowing regions. Vineyard managers have adopted various strategies for managing GLRD, including roguing individual symptomatic vines and replacing them with certified vines derived from clean, virus-tested stocks; applying insecticides targeting mealybug vector populations to reduce disease spread and minimize long-term impacts; and fully replanting vineyards at the onset of disease symptoms. Moreover, some managers elect not to control GLRD at all. We collected survey data from vineyard managers throughout the three major California grapegrowing counties, Napa, Sonoma, and Northern San Joaquin Valley, to estimate the economic impact of GLRD on Cabernet Sauvignon vines. The goal was to identify cost-minimizing management strategies under various disease-prevalence levels, price penalties, timing of disease onset relative to vineyard age, yield losses, and costs of control. Our results estimated that the economic cost of GLRD ranged from $29,902 to $226,405 per ha. Roguing symptomatic vines and replanting with certified vines in combination with insecticides to reduce mealybugs may minimize losses if GLRD prevalence is low (between 5 and 10%), while a full vineyard replacement should be pursued if disease prevalence is higher, generally above 25%, although regional differences were noted. These findings should help vineyard managers in the three regions examined to adopt optimal GLRD management strategies that can be tailored regionally or locally to unique market opportunities, potential market prices, and annual operating costs.

Key words: grapevine leafroll disease, GLRD, Napa County, Sonoma County, Northern San Joaquin County, net present value, roguing, vine replacement, mealybugs, economic impact

Grapevine leafroll disease (GLRD) is a viral disease found across all grapegrowing regions worldwide. GLRD can have devastating effects on yield (up to 30 to 68% reduction in yield) and grape quality, including delays in ripening, reduced accumulation of total soluble solids (Brix), increased acidity, reduced tannin content in berry skin, and irregular or undesirable flavor profiles (Goheen and Cook 1959, Martelli and Boudon-Padieu 2006, Martinson et al. 2008, Naidu et al. 2014).

GLRD is caused by five grapevine leafroll-associated viruses (GLRaVs) named GLRaV-1, -2, -3, -4, and -7. These viruses are primarily introduced to vineyards through infected budwood and plant materials. GLRV-1, -3, and -4 are also vectored by two insect families in the order *Hemiptera*, namely, *Pseudococcidae* (mealybugs) and *Coccidae* (scales and soft scales) (Engelbrecht and Kasdorf 1990, Golino et al. 2002, Naidu et al. 2014, Sforza et al. 2003). More specifically, mealybugs of the genera *Heliococcus, Phenacoccus, Planococcus,* and *Pseudococcus*; soft scale insects of the genera *Pulvinaria*, *Neopulvinaria*, *Parthenolecanium, Coccus, Saissetia,* and *Parasaissetia*; and scale insects of the genus *Ceroplastes* have been reported to transmit GLRaV-1, -3, and-4 (Naidu et al. 2014).

Several species of mealybugs in California have been shown to transmit GLRaV-3, including grape mealybug (*Pseudococcus maritimus* [Ehrhorn]), vine mealybug (*Planococcus ficus* [Signoret]), and less commonly, the obscure mealybug (*Pseudococcus viburni*) (Almeida et al. 2013, Daane et al. 2008). These vectors are present throughout the major grapegrowing regions of northern, central, and southern California (Daane et al. 2008). Globally, a wide range of soft scale and mealybug species vector the disease, and these include essentially all those species that are commonly found in regions

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where GLRD is of concern (Almeida et al. 2013). Viruliferous mealybugs are mainly dispersed through wind, machinery, and field workers, but also by other means (Almeida et al. 2013).

Vineyard managers adopt various strategies for managing GLRD, including minimizing its spread. These strategies include roguing individual symptomatic vines and replacing them with certified planting material derived from virus-tested, clean vines. They also include insecticide treatments targeting mealybugs to reduce disease spread and minimize its long-term impacts. Some managers may choose to fully replant the vineyard at the onset of disease symptoms. And some may decide to tolerate the disease and the associated impacts on yield and quality and not control GLRD. Clearly, disease management strategies depend on a number of parameters that affect short- and long-term economic damages, including reduced yields, possible penalties to grape quality, and costs of controlling the disease (insecticide sprays, roguing labor, and material costs).

Only a few studies have investigated the long-term economic impact of GLRD. Using a model of virus spread under three infection scenarios, a study by Walker et al. (2004) indicated that New Zealand vineyards experience a per-hectare reduction due to GLRD of USD $21,000 by growing years 12, 15, and 17. Nimmo-Bell (2006) compared the net present value (NPV) of diseased and healthy blocks of Merlot and Sauvignon blanc in New Zealand under the following three different disease management strategies: total vine removal, roguing and replacing symptomatic vines, and roguing and replacing symptomatic vines as well as those immediately adjacent to them. Compared with no intervention, roguing and replacing symptomatic vines reduced the disease impact 6-fold in both cultivars (Nimmo-Bell 2006). A 2010 study in the Finger Lakes region of New York found that the estimated impacts of GLRD on Cabernet franc could be substantially reduced if initial prevalence of GLRD is moderate (between 1 and 25%) and roguing and replanting was undertaken (Atallah et al. 2012). The same study found that the absence of any control method could result in economic losses ranging from $25,000 per ha, for a 30% yield reduction and no grape quality penalty, to over $40,000 per ha for a 50% yield reduction and a 10% penalty for poor fruit quality. Atallah et al. (2012) concluded that replacement of the entire vineyard was the optimal strategy when GLRD prevalence was greater than 25% and when vineyards managers would otherwise incur a 10% quality penalty.

This study addresses the optimal management strategies for controlling GLRD in California. We collected survey data from managers throughout the counties in Central California and the North Coast, Northern San Joaquin Valley (mainly in and around the Lodi area), and the south central coastal region to estimate the economic impact of GLRD on Cabernet Sauvignon. We also sought to identify cost-minimizing management strategies under various levels of disease, price penalties, yield losses, and costs of controlling the disease. We selected Cabernet Sauvignon because this cultivar is grown in each region considered in this study. Moreover, it exhibits visible GLRD symptoms such as deeply red leaves contrasted with green veins and a blade that is often curled. Without the same visible symptoms in white cultivars, detecting GLRD can be more difficult and the disease may more easily go undetected.

Using an NPV approach, we analyzed the outcomes of several GLRD control strategies, including full vineyard removal and roguing and replanting symptomatic vines with and without insecticide treatment. We also analyzed a scenario of no GLRD control. In addition, a few growers discussed plans to fallow land because they suspected that their soil harbored residual sources of virus inoculum (i.e., remnant vine roots). Given that this strategy for managing GLRD was uncommon and that the pathways between remnant roots and GLRD infection are still under investigation, we did not consider this strategy in this study. After identifying common management approaches, we then identified those that minimized disease costs under the conditions and scenarios described. Here we report findings for three counties including Napa, Sonoma, and the Northern San Joaquin Valley (NSJV), for which sufficient information on establishment cost and vineyard production data were available.

Materials and Methods

Surveys. Multiple virus species associated with GLRD are found in California. While the models involved and analysis undertaken in this work were primarily concerned with virus species that are insect-vectored (specifically, GLRaV-1, -3, and -4), the results reported here can also be useful for growers affected by GLRaV-2 or -7, despite the fact that these viruses have no known insect vectors. In California, GLRaV-3 poses a particular threat to winegrape-growing regions focused on high-quality production, including the Napa Valley (Sharma et al. 2011, Almeida et al. 2013).

To construct realistic scenarios and identify representative parameters, surveys were designed and conducted with winegrape farm managers in California whose vineyards had been affected by GLRD (see Supplemental Appendix 1). Grape buyers in California were also surveyed to understand the quality characteristics and associated price differential (penalty) for low-quality grapes.

Although some California farm managers manage a single vineyard, it is more common for a grower to own—or be hired by—a larger vineyard management company. As a result, a single grower may be responsible for cultivating grapes on several vineyards in a given region. This management is often done on behalf of corporate or individual property owners, winemakers, or both. We thus broadly refer to this diverse group of growers and managers who are in charge of winegrape cultivation as “vineyard managers.”

Given these different types of management systems, an individual vineyard manager may face varying levels of GLRD infection within vineyard blocks and among different vineyards managed. For consistency, we asked vineyard managers to describe three blocks where they were actively managing GLRD and to respond to questions about disease prevalence, disease history, and quality and yield impacts in these blocks. The vineyard managers then answered a series of questions related to marketing, including quality standards, average prices, potential price penalties, and grape rejections. They also responded to questions about alternative market opportunities for grapes low in sugar, high in acidity, or of substandard color. The data from this survey were used for the development of disease management scenarios.

In total, 24 vineyard managers and buyers in NSJV, Napa, and Sonoma counties participated in this study. Even though all of these regions are managing GLRD, we found that vineyard managers operating within these counties had a diverse range of priorities and perspectives related to expected and actual grape prices, acceptable quality levels, and unique quantity thresholds required for farm profitability. These factors describe regionally specific economic conditions that inevitably demand unique disease management strategies and approaches.

Parameters. *GLRD prevalence*. Vineyard managers in California reported that initial infection levels (the levels of infection at the time that management for GLRD began) were between 5 and 80%. Many respondents suggested that they tended to consider total vineyard replacement when initial infection levels were above 40%. This threshold of initial infection for vineyard replacement is supported by the study of Atallah et al. (2012), which concluded that the optimal GLRD management strategy for vineyard managers in the Finger Lakes region of New York was to replace the entire vineyard rather than rogue individual vines when the initial disease prevalence was above 27%. The same study found that the economic impact of a more moderate GLRD infection rate, between 1 and 27%, was minimized when vineyard managers pursued a strategy of roguing individual vines. Taking into account these observations, we estimated models from initial prevalence levels of 5, 20, and 40% to identify the threshold of initial disease prevalence that warrants a change in the GLRD control strategy for managers in our study regions.

Spread of GLRD. The literature evaluating the annual spread (or rate) of the disease was reviewed to find regionally appropriate estimates. Given the complexity of GLRD due to the interactions between vine age, climate, varietals, potential vectors, and local reservoirs of insect vectors, regional average rates of GLRD disease spread are highly variable (Arnold et al. 2012, Almeida et al. 2013, Pietersen 2006). Golino et al. (2008) reported that GLRD prevalence in California vineyards increased over 5 years by close to 10% annually. Their estimate is consistent with the results of the comparative study conducted by Arnold et al. (2012), which showed that the annual disease spread for California closely tracks the average of 11% annual spread. We therefore used this 11% annual rate of disease diffusion in our simulations.

Yield reduction due to GLRD infection. Few managers measured yield reductions due to GLRD infection, but nearly all of those surveyed noted that yields in an infected block were consistently lower than in similar, healthy blocks. Most managers suggested that GLRD-associated yield reductions were anywhere between 15 and 70%, with an average yield reduction at around 25%. A review of the available literature suggested that GLRD commonly reduces yield by 30 to 60% (Atallah et al. 2012). On the basis of these findings, the following two values of yield reduction were considered: 25% and 40%.

Quality impacts. We expected clear contractual standards outlining sugar, acidity, and other fruit qualities, such as fruit skin color, to be strictly enforced between buyers and sellers. Although sugars were most certainly expected to meet a range for a particular cultivar, deducing exact price penalties or bonuses for decreased or increased Brix proved to be difficult. Managers and buyers mentioned a more flexible system where contractual standards served as guidelines to navigate a grower's unique agricultural context, respond to overall market conditions, and address a specific bottling program objective or winemaker preference. In general, we found that most vineyard managers in Napa County were targeting the ultra-premium market, those in Sonoma County were targeting the mid-to ultra-premium market, and NSJV managers were targeting the premium market. In each county, one could find a number of exceptions to these observations, but this rough classification helps contextualize the common market dynamics that often drive quality expectations and volume targets.

Most participants responded that buying and selling grapes was a difficult undertaking and involved fostering stable, trustworthy trading relationships. This was especially true in Napa County, where final agreement between grape buyers and sellers (growers) about sale price tended to include a discussion and review of grape quality at the time of harvest. At this point, prices might be negotiated up or down, depending on previous contract price, quality markers, and immediate supply needs.

In NSJV, managers suggested that the prior year's price was used as a benchmark and that "sugar bonuses" (or other positive or negative attributes) would allow for a percentage above or below that baseline figure. Although there was little agreement on exact penalties for reduced Brix, a subset of vineyard managers suggested two possible price penalties stemming from quality issues: (a) no penalty if market dynamics worked in their favor and (b) a reduction of 5 to 10% per 1 Brix below the target range specified in the contract. On average, vineyard managers in Napa and NSJV counties estimated typical 1 to 2 Brix reductions for vineyards infected with GLRD. Therefore, in our simulations, we used a quality penalty of 10% per 1 Brix.

Methods of GLRD control. Survey respondents in California pointed to one of four strategies for managing GLRD. They included leaving GLRD unmanaged, roguing and replacing individual (symptomatic) vines, replacing whole infected vineyard blocks, or combining roguing with insect vector control through chemical treatments.

Linking reductions in viral prevalence and overall disease spread with a specific management practice required us to root our assumptions in the available literature whenever possible. Notably, few studies have explicitly linked certain disease management strategies to reductions in overall disease prevalence or improved volumes (i.e., minimized crop losses) under disease and pest conditions; these studies include those by Daane et al. (2008), Pietersen et al. (2013), and Atallah et al. (2012).

For roguing, reductions in annual disease incidence were estimated by using the findings of a South African study (Pietersen et al. 2013), which suggested a range of roguing efficiency (i.e., assessed as annual reduction of disease incidence) of 15 to 30% annually. A New York study by Atallah et al. (2012) assumed a 50% reduction in GLRD incidence when roguing was employed to account for infected, asymptomatic vines remaining in the vineyard. This model assumed that GLRD spreads solely by planting infected vines rather than through vector transmission of GLRaVs within a vineyard. On the basis of these findings, discussions with UC Cooperative Extension farm advisors, and knowledge that California winegrowing regions were largely combating GLRD caused by the transmission of GLRaVs by mealybugs, our simulations assumed that roguing reduces the GLRD disease prevalence annually by 25%.

In California, GLRaV-3 is vectored by grape mealybug, which commonly is prevalent throughout the winegrape-growing regions of California, including in our study areas of interest. The recently introduced vine mealybug, which can also vector GLRaV-3, is more prevalent in the San Joaquin Valley. California farm advisors and other experts in Napa County indicated that the vine mealybug is present in pockets throughout the area, specifically, in the Carneros region. Strategies to control this insect include a combination of roguing and insecticide applications targeting mealybugs. Chemical control measures are selected and timed to maximize efficacy by targeting the developmental stages of each vector. In addition, these measures are weighed against the presence of natural enemies (Almeida et al. 2013, Golino et al. 2008). As a result, we considered a range of insecticide and mealybug management costs, ranging from around $123.50 per ha, to treat a grape mealybug population that is partially kept under control by natural enemies, to $370.50 per ha to treat vine mealybug that has no resident natural enemies, with the exception of a predaceous beetle and the parasitoid, *Anagyrus pseudococci*, a resident of the southern Central Valley. For simulation purposes, an average cost of $272.00 per ha for controlling mealybug was used (Table 1). In the discussion to follow, we describe how variation in this cost (as some respondents suggested a figure closer to $2,470 per ha) dramatically affects estimated production costs.

Scenarios to assess GLRD impact. Six scenarios were used to assess disease impacts and optimal management strategies (Table 2). The scenarios were constructed to create a decision matrix that vineyard managers could implement to optimize disease management practices in light of variable biological conditions (such as disease prevalence and potential yield reductions), available managerial options (disease control measures including no control, roguing at particular prevalence levels, and entire vineyard replacement), and economic parameters (average price paid for grapes and quality penalties of 10% per 1 Brix). The identification of optimal management strategies was the outcome of the analysis.

Scenario 1: Baseline, no GLRD. The baseline scenario considered the cash flow from a 1-ha vineyard over 25 years old with no GLRD. A baseline scenario was run for a representative vineyard in Sonoma, NSJV, and Napa counties, using sample cost data of winegrape production from the 2012 North Coast Region, Napa County cost studies (Cooper et al. 2012). Production (as average regional yield estimates) and per-ton prices were estimated for each county with the

Table 1 Description of critical parameter inputs.

Key variables	NSJV region	Sonoma County	Napa County
Production			
Land cost + land preparation per ha ($)	43,380.61	214,074.90	346,775.65
Annual operating costs beyond year 3 per ha ($)	5,4321.53	9,247.68	13,977.73
Average tons after year 4 per ha	24.70	12.35	11.12
Rogue & replant cost per vine ($)	14.60	14.60	14.60
Cost of insecticide spray (mealybug) per ha ($)	272	272	272
Number of vines per ha	1956	2690	3841
Price			
Average price per metric ton in 2012 ($)	668	2,036	4,533
Cost of capital (%)	5.75	5.75	5.75

Table 2 Description of disease control scenarios.

	Initial infection (%)	Yield reduction due to leafroll (%)			Quality penalty (% loss per Brix below)	
Managerial decisions		0	25	40	None	10% price reduction for 1 Brix
No management—annual disease progression of 11%	5, 20, or 40		X[a]	X	X	X
Full vineyard removal and replacement at year 4 and year 10	5, 20, or 40		X	X	X	
Roguing and replanting diseased vines	5, 20, or 40	X			X	X
Roguing and replanting diseased vines, vector control	5, 20, or 40	X			X	X
Late onset of the disease (onset in year 12)	5, 20, or 40		X	X	X	X

[a]X denotes that that particular scenario was analyzed and discussed in this study.

2012 Grape Crush Report issued by the California Department of Food and Agriculture (CDFA) and the U.S. Department of Agriculture (USDA) (California Dept. of Food and Agriculture 2012). The difference between the NPV from this baseline scenario and the NPVs from scenarios with different leafroll management strategies estimated the economic impact of GLRD for each scenario.

Scenario 2: GLRD progression with no control of the disease. In this scenario, GLRD is introduced in the vineyard in year 1 and subsequent spread is based on the logistic model suggested by Charles et al. (2009) and Atallah et al. (2012). In this scenario, managers do not rogue, replace, or spray in response to the disease. Four scenarios considered yield reductions of 25% and 40% with no price penalty, and a 10% price penalty for quality. The NPVs for these scenarios estimated how price penalties and yield reductions can influence management decisions.

Scenario 3: Full vineyard replacement. In this scenario, the vineyard manager decides to replant the entire vineyard at the onset of symptoms in year 3, reflecting the uncertainty of working with GLRD, given the possibility that the viruses might continue to be transmitted by mealybugs and that yields and quality might decrease. The NPV from this scenario was used as a benchmark to identify the threshold incidence that warrants replacement of the entire vineyard as opposed to roguing of individual vine.

Scenario 4: Roguing and replanting vines. These scenarios looked at the economic impact of roguing symptomatic vines at the four aforementioned disease-incidence levels. We used a roguing and replanting cost of $14.60 per vine, which includes materials and labor costs, but not costs of identifying the disease (Stewart and Klonsky 2012). In this scenario, roguing commences the year after vines start showing symptoms (i.e., in year 4). Because some infected vines are asymptomatic, we assumed that roguing and replanting reduces disease prevalence by only 50% each year and that the disease is never eradicated but kept at a 1% infection level at best. Initial GLRD prevalence levels of 5, 20, and 30% were used to identify the critical infection levels that make full vineyard replacement a more economically attractive proposition than roguing individual vines.

Scenario 5: Roguing and replanting vines, and spraying insecticides to control vectors. These scenarios looked at the economic impact of roguing combined with controlling vectors with chemical treatments. We used a per-hectare average cost of $271.70 for the control of grape and vine mealybugs based on the range of costs for insecticide treatments outlined in the University of California Davis Integrated Pest Management Guidelines for Grape and on interviews with extension farm advisors and winegrape managers (UC Integrated Pest Management Program 2013). Interviews with local farm advisors suggested a range of $123.50 per ha, for treating grape mealybug in the NSJV, to more than $1,235 per ha, for a grower in Napa County who is using biological control, spraying, and utilizing other integrated pest management methods. In our survey, we found that many vineyard managers were using spirotetramat (Movento) or imidacloprid and buprofezin (Admire and Applaud), each of which costs approximately $296 per ha (Daane et al. 2008, extension agent interviews 2013). A sensitivity analysis that included a wider range of vector control costs is considered in a further section.

Scenario 6: Late onset of the disease. In this scenario, GLRD is introduced through insect vectors late in the vineyard lifespan, during year 12. We estimated the NPV for different initial infection levels (5, 20, and 40%), yield reductions (25% and 40%), and the aforementioned strategies for controlling GLRD, including roguing, roguing plus insecticide for vector control, vineyard replacement, and a no-control response. These scenarios were evaluated to identify a possible vineyard age beyond which no intervention would be recommended, given a vineyard lifespan of 25 years.

Economic analysis. The NPV analysis provides a useful tool for calculating and comparing alternative investments when the cost and resulting cash flows of these investments vary over time. A positive NPV suggests that the investment has not only paid for itself (i.e., the investment cost has been recouped), but that it has also provided a return on this investment. A negative NPV suggests that when the cash flows are discounted back to present-day dollars, the investment has not been recouped, and the endeavor is unprofitable. In this case, we evaluated how investments in variable disease management strategies compare over the economic lifetime of a California vineyard (25 years). An NPV per hectare was calculated for each GLRD control scenario over the economic lifetime of a California vineyard. The NPV calculations were based on cost data for vineyard establishment reported in the county cost studies of Sonoma, Napa, and NSJV (see Smith et al. 2010, Cooper et al. 2012, and Verdegaal et al. 2012, respectively). Each cost study includes the average reported costs, revenues, and financial assumptions of winegrape vineyard managers. This information was augmented and verified by our 2013 survey, in which we collected information on actual prices paid, average yields, and other relevant information (see Supplemental Appendix 1). Average Cabernet Sauvignon prices for the relevant regions (NSJV and Napa and Sonoma counties) were taken from the 2012 Annual Crush Report, published jointly by the CDFA and the USDA (California Dept. of Food and Agriculture 2012).

The NPV of various GLRD control scenarios is a function of the annual quantity (in tons) of grapes per hectare produced when considering the prevalence of GLRD infection, the annual cost of producing grapes and managing GLRD, and the average regional price of grapes per ton across a 25-year vineyard lifespan. The discount rate (as cost of capital) was held constant at 5.75%. Given these variables, each GLRD scenario had a unique NPV, which could then be compared to the NPV of no control of GLRD. The optimal strategy under various GLRD-incidence levels was identified as that with the highest NPV.

The economic impact of GLRD was calculated by taking the difference between the NPV of a healthy vineyard and the NPVs of scenarios evaluating different GLRD control methods in diseased vineyards. The optimal strategy was identified as that scenario that minimized the NPV difference between a healthy vineyard block and a diseased vineyard block.

Results

Regional viticultural characteristics and Cabernet Sauvignon fruit prices. Red winegrape production in the NSJV is one of the largest in the state of California, with over 453,690 metric tons of red winegrape varieties produced in 2012 (California Dept. of Food and Agriculture 2012). NSJV is largely focused on providing high volumes of consistent-quality grapes, often for the premium wine market. Napa and Sonoma counties, both located in the North Coast region, have substantially smaller annual production; in 2012, Napa County and Sonoma County produced ~119,822 and 146,670 metric tons of red wine varietals, respectively. Napa County is famously known for providing ultra-premium winegrapes with unique flavor notes and quality profiles, which may be rewarded with high prices by small-scale, niche winemakers. In 2012, the average price for Napa-grown Cabernet Sauvignon was about seven times higher (~$4,533 per metric ton) than the average price of the same variety grown in NSJV (~$668 per metric ton) (California Dept. of Food and Agriculture 2012). Between these price extremes in these two locations lies Sonoma County, whose growers produce for a mix of premium, mid-premium, and ultra-premium markets. Average prices for Cabernet Sauvignon grapes grown in Sonoma County in 2012 reached $2,036 per metric ton.

Modeling disease spread. Using an 11% annual rate of disease diffusion in the simulations, we found that at an initial GLRD infection of 5% of vines starting in year 3 (the first year when visual symptoms become apparent to a vineyard manager when the infections do not originate from contaminated planting material), disease prevalence in a vineyard in Napa, Sonoma, or NSJV will reach more than 50% by year 9 and close to 100% by year 25. With an initial infection level of 20 or 40%, over half of the vines were predicted to be infected by years 7 and 5, respectively, with almost complete infection by year 25.

GLRD economic impact and optimal disease management strategy. In the regions evaluated, and under the baseline of no disease control, economic losses due to GLRD over the lifetime of a 1-ha (2.47 acres) block of Cabernet Sauvignon ranged from $29,902 in NSJV with a 5% initial infection, 25% yield reduction, and no quality penalty, to over $226,405 for a 40% infection, 40% reduction in yield, and a 10% price penalty for reduced quality in Napa (Table 3). On average, a 10% price penalty for low-quality grapes across regions, initial infection levels, and average yield reductions further increased economic losses by 22 to 34%.

Largely because of the cost of land and labor, the initial costs for establishing a vineyard in Napa County are significantly higher than those incurred in Sonoma County and in NSJV (Cooper et al. 2012). Using the average price for Cabernet Sauvignon and the establishment and production costs (Cooper et al. 2012), we estimated the NPV from a healthy 1-ha vineyard in Napa to be $43,950. According to the estimated production costs in 2010 and 2012 for Sonoma County and NSJV (Smith et al. 2010, Verdegaal et al. 2012), the NPVs of healthy 1-ha vineyards were estimated to be −$28,446 and $68,325, respectively. Annually, however, these figures may be drastically higher or lower (positive or negative), due to seasonal and regional variations, yearly price fluctuations, or markets targeted or due to changes in the assumptions that are currently outlined in the vineyard establishment and cost studies.

Napa County. *Roguing vines and controlling vectors versus roguing only.* When the disease onset occurred in year 3 and the initial infection was between 5 and 26%, the optimal management decision was to rogue diseased vines, replace them, and treat virus vectors. Based on our assumptions, in Napa County, it was always preferable to rogue and replace vines and treat vectors rather than to only rogue and replace. This held true even if a vineyard manager faced an aggressive mealybug population that resulted in higher costs for vector control of up to $1,235 per ha. Only when per-hectare costs of vector treatment exceeded $1,482 did roguing only become a

Table 3 Net present value of GLRD control scenarios (e.g., GLRD spread with no management) under different yield reduction (25 and 40%) scenarios, quality penalties (no penalty or 10% reduction in average price), and three initial infection levels (5, 20, and 40%) beginning in year 3.

	GLRD economic impact[a] for NSJV region		GLRD economic impact for Sonoma County		GLRD economic impact for Napa County	
Treatment scenario	Economic impact with 25% yield reduction ($/ha)	Economic impact with 40% yield reduction ($/ha)	Economic impact with 25% yield reduction ($/ha)	Economic impact with 40% yield reduction ($/ha)	Economic impact with 25% yield reduction ($/ha)	Economic impact with 40% yield reduction ($/ha)
No control, 5% initial infection, no quality penalty	29,902	47,843	45,445	72,712	90,987	145,579
No control, 20% initial infection, no quality penalty	33,353	53,366	50,514	80,822	100,996	161,594
No control, 40% initial infection, no quality penalty	37,956	60,729	57,272	91,635	114,342	182,948
No control, 5% initial infection, 10% quality penalty	47,617	63,764	71,919	96,460	143,640	192,773
No control, 20% initial infection, 10% quality penalty	50,723	68,734	76,481	103,758	152,649	207,187
No control, 40% initial infection, 10% quality penalty	54,865	75,361	82,563	113,490	164,660	226,405

[a]See descriptions of scenarios in Table 2.

more economical treatment (we did not evaluate a scenario of only managing mealybug infestation without roguing). However, above an initial infection rate of 26%, vineyard replacement was the optimal disease management strategy. In Table 4, we present a decision matrix that suggests optimal disease management strategies for all three counties under these various quality penalties, infection rates, and yield losses.

Late vector-mediated GLRD. Efficient management responses to late, vector-mediated virus infection in Napa County vineyards may have minimized losses by vineyard replacement if initial GLRD prevalence level exceeded 25% in year 12. If onset occurred in year 12 with lower levels of initial infection (15% or less), the optimal strategy was to rogue and replace vines and to treat vectors.

The optimality of the no-control strategy for certain parameter combinations should be interpreted with caution. For example, we found that during late onset of GLRD in year 12 with an initial infection level of 15 to 25%, it was economically optimal to pursue a no-control strategy. In this scenario—at an infection level of over 25%—replanting became more optimal than inaction. As the disease progresses, most managers will face quality and reputational risk, including, as we were told, the loss of contracts if successive harvests yield poor-quality grapes and result in diseased vineyard conditions. Our simulation results did not account for this risk nor did it account for the damage imposed by a no-control strategy on neighboring vineyard blocks. The optimal strategy under a price penalty of 10% in Napa County when disease onset took place in year 12 was to rogue vines and treat vectors when initial GLRD infection levels were between 5 and 16% and to replace the entire vineyard when the initial infection level was above 16%. Later disease onset in year 12 caused vineyard replacement to be optimal at an initial prevalence of GLRD of 11%.

Sonoma County. *Roguing versus roguing and controlling insect vectors.* For scenarios with GLRD-induced yield losses of 25 and 40%, and an initial infection level between 5 and ~20%, the optimal strategy was roguing and replanting vines and treating vectors (Table 4). Above the 20% initial infection threshold, vineyard replacement was the optimal strategy.

Late vector-mediated GLRD. Without a price penalty, vineyard replacement in Sonoma County was not optimal when the disease onset occurred in year 12, regardless of the infection levels or yield impacts considered. Losses incurred by total vineyard replacement outweighed the disease impacts, and costs experienced later in the vineyard lifecycle were never recouped. In fact, when late onset of the disease occurred, we identified a small, shrinking window for managing GLRD between an initial infection rate of 5 and 12% with onset in year 12. In this initial infection range, the optimal strategy was to rogue and replant vines and to treat vectors.

High costs of vineyard establishment and replanting that can never be recouped make vineyard replacement late in a 25-year projected lifespan suboptimal. However, if a vineyard manager in Sonoma County faced a 10% price penalty due to poor quality of GLRD grapes, vineyard replacement became a more economical choice (Table 4). Accordingly, above an initial infection level of 15% (if disease onset occurred in year 12), managers facing a 10% price penalty should opt to replace the entire vineyard.

San Joaquin Valley County. *Roguing versus roguing and controlling insect vectors.* Farm advisors in NSJV underlined the urgency of controlling vine mealybug, a relatively newly introduced and aggressive pest in the region. Costs for vector control ranged from $124.00 to $247.00 per ha for grape mealybugs and from $123.50 to $370.50 per ha for vine mealybugs. As previously mentioned, we used an average control cost of $271.70, which included both labor and material costs.

With an initial infection rate in year 3 between 5 and 20% (and assuming yield losses of 25%), the optimal GLRD management strategy was to rogue and replant vines and to treat insect vectors (Table 4). Above an initial infection rate of 20 to 25%, vineyard replacement was the most economically attractive strategy. When we considered GLRD yield losses of 40% or more, the strategy of roguing and replanting vines and treating vectors became optimal up to an infection prevalence of 18%. Above an initial infection rate of 18%, vineyard replacement became the optimal strategy.

Table 4 GLRD control decision matrix for a Cabernet Sauvignon vineyard according to region, disease onset (year), and price penalty.

Annual yield reduction	Disease onset in year 3, no penalty			Disease onset in year 3, 10% quality penalty			Late disease onset (in year 12), no quality penalty			Late disease onset (in year 12), 10% quality penalty		
	Napa County	Sonoma County	NSJV region	Napa County	Sonoma County	NSJV region	Napa County	Sonoma County	NSJV region	Napa County	Sonoma County	NSJV region
25%												
5% infection	RRVC[a]	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC
20% infection	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	No control	Replace	Replace	Replace	Replace
40% infection	Replace[b]	Replace	Replace	Replace	Replace	Replace	Replace	No control	Replace	Replace	Replace	Replace
40%												
5% infection	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC	RRVC
20% infection	RRVC	RRVC	Replace	RRVC	Replace	Replace	No control	No control	Replace	Replace	RRVC	Replace
40% infection	Replace	Replace	Replace	Replace	Replace	Replace	Replace	No control	Replace	Replace	Replace	Replace

[a]RRVC = Rogue, replant, and vector control.
[b]Replace = Total vineyard replacement.

Late vector-mediated GLRD. Models describing a late onset of the disease (beyond year 12) indicated that in the absence of a price penalty on quality, vineyard replacement in response to GLRD was not optimal. If the disease onset occurred in year 12 and the initial infection rate was less than 16%, the optimal management strategy consisted of roguing and replanting vines and controlling vectors. Above an initial infection prevalence of 16%, vineyard replacement was optimal in the presence of a quality penalty. For NSJV, late onset of the disease presented limited opportunities for economical management. With disease onset in year 12, the infection rate at which a vineyard should be replaced was 17%. If a price penalty for quality was incurred, pursuing a strategy of vineyard replacement was even more economically attractive. As discussed in the section on Sonoma County, many managers would replant with the expectation to get much more than 8 years of productive value out of an investment into vineyard replacement.

Discussion

This study builds on research undertaken in New York (Atallah et al. 2012) by estimating the per-hectare economic impact of GLRD under various management strategies in three distinct regions of California wine country. Earlier studies recommended controlling GLRD by roguing and replanting symptomatic vines and estimated the threshold at which roguing and replanting vines is preferable to a total vineyard replacement (Freeborough and Burger 2008, Nimmo-Bell 2006, Walker et al. 2004, Atallah et al. 2012). This study contributes to this body of work by considering a third option: roguing and replanting symptomatic vines and controlling vectors of the disease.

In this study, we found that in California, roguing and replanting vines and controlling vectors is always superior to roguing alone. Even in Napa County, where the costs of production and GLRD disease pressure from vectors are high, controlling vectors and roguing and replanting symptomatic vines minimized the economic impact of GLRD. This was true even when insecticide applications and materials costs quadruple from our assumed cost of $271.70 to $1,235 per ha. Across regions, the economic tipping point for switching management strategies (from roguing and replanting diseased vines and vector control to either vineyard replacement or no control) is an initial infection rate of 20 to 40%. More often than not, the optimal choice for a vineyard manager dealing with GLRD is either roguing and replanting vines and controlling vectors or replacing the infected vineyard. It is important to note that our study did not evaluate viruliferous vectors as a possible GLRV infection pathway. Future research should consider how adoption of effective vine removal protocols could be optimized for managers who might face GLRD infection from possible residual sources of virus inoculum (e.g., remnant vine roots).

For Napa and Sonoma counties and for NSJV, roguing and replanting vines and treating insect vectors was the optimal strategy for managing GLRD at lower levels of initial infection (between 1 and 26%). For all regions, the threshold for replanting was between GLRD infection levels of 11 and 26%. We found that vineyard managers in Napa County have the largest initial infection range (between 5 and 26%) in which roguing and replanting vines and treating vectors is the optimal strategy. By comparison, vineyard managers in NSJV had the smallest initial infection range (~20%) for treating vectors and roguing before the threshold for vineyard replacement is crossed.

It is well known that California wine country is a diverse region in terms of climate, production costs, varieties grown, and available markets pursued. For example, average prices for Cabernet Sauvignon grapes in Napa County are more than six times higher than the same grapes grown in NSJV. It is thus unsurprising that the two regions have unique growing conditions, costs of cultivation, and potential quality penalties that drive practices for controlling GLRD. What is perhaps surprising is that the same strategies offered the highest NPV whether the grapes are grown for a specific premium market, as is often the case in Napa County, or are cultivated for the premium market, as is often the case in NSJV. The only difference was the threshold at which it is better to replace the vineyard rather than to rogue and replant vines and to treat vectors. At an initial GLRD infection level of 20%, an NSJV vineyard manager maximized the NPV by replacing the entire vineyard; a Napa County vineyard manager would have undertaken the same strategy if the initial GLRD infection was above 26%. However, a limitation of this study was that we likely did not fully account for the quality penalty (i.e., a price penalty of more than 10%) that growers in Napa might face. Managers indicated that poor-quality grapes could cost them annual contracts; discourage contract renewal; or erode important relationships with buyers, winemakers, or even customers. According to interviews, managers in Napa who faced GLRD were often the quickest to replace vineyards even at infection levels much lower than 26%.

Managers in each of these regions face very different market forces that favor different farming practices and thus influence disease management strategies. For example, regarding management practices, vineyard managers in the NSJV respond to a regional market that prioritizes volume targets and encourages machine harvesting and growing techniques for maximizing yields. As a result, many managers surveyed in that region indicated that price reductions in quality were only experienced at extremely high levels of GLRD infection. That is, when poor-quality grapes from a GLRD block skewed the Brix average overall (which we found to be rare) or when overall yield losses accumulated to unbearably high levels. For NSJV, if vineyard managers met their grape volume targets, they were often unconcerned about GLRD. Given the low profit margins, the need to meet volume targets, and the reluctance to devote additional labor hours and monies to roguing out individual vines, roguing and replanting in response to GLRD seemed to occur rarely. As a result, one can assume that many NSJV managers have an incentive to wait until GLRD infection becomes rampant before deciding to replant vines, a practice that may lead to viral spread to neighboring or outlying vineyards.

Conversely, managers in Napa County (and some in Sonoma County) were primarily concerned with quality. These managers reported that they were willing to reduce (or endure) yield losses accrued through individual roguing and replanting, so long as quality was safeguarded. The risk of price penalties and non-renewed contracts as a result of quality concerns caused many managers to practice roguing and replanting. Ultimately, California seems to be characterized by two different business models that have interesting applications for GLRD control: one model that maximizes farm profitability via low margins and high yields and another that maximizes farm profitability via high margins and low yields. This suggests fundamentally different motivations for managing GLRD and evaluating the success of a particular strategy.

It is important to note that any optimality of pursing a no-control strategy ignores significant negative effects, including inter-vineyard disease transmission via mealybug vectors. Essentially, a no-control strategy in one vineyard imposes a direct transmission externality on neighboring vineyards. In turn, the cost-effectiveness of control strategies in these vineyards might be compromised (Atallah et al. 2013). In addition, use of a no-control strategy may also generate uncertainty in long-term contract negotiations or renewals with winegrape buyers. Our analysis assumed a fixed 25-year lifespan, but the useful lifespan of a vineyard is likely to be more variable. Vineyard managers are likely more flexible about when to replace a vineyard. They might consider replacement in the later years of a particular block and fully expect to recoup replanting costs.

Although this study sheds light on the economic impact of GLRD, its results should be interpreted with caution. Our analysis assumed averages across a diverse group of growers, terrains, and markets. Moreover, patterns of disease spread used in this study were taken from regional averages (Arnold et al. 2012, Golino et al. 2008), but are known to be variable because of a number of unknown and unique ecological, biological, and production factors. The model may have underestimated economic impacts, especially if the rate of viral spread is higher than the rate used in this study. Future research could refine our findings by evaluating the rate of GLRD spread in California vineyards with more accuracy. Similarly, we found limited empirical evidence outlining the interaction between the rate of GLRD spread and the implementation of certain GLRD management practices; namely, how the strategy of roguing, replanting, and mealybug control affects GLRD spread. Estimating the impact of this particular strategy is important as most managers point out that they are using this combined approach for faster reduction in disease spread. Studies examining the efficacy of various methods and strategies for controlling GLRD spread are only just emerging (Arnold et al. 2012, Daane et al. 2008, Golino et al. 2008).

Conclusions

The results of this research provide vineyard managers in Napa and Sonoma counties and in NSJV in California with valuable estimates of the economic impact of GLRD and suggest optimal management strategies to control the disease. Moreover, this study provides an analysis of the cost of managing this disease—specifically, how the optimality of various disease management strategies depends on a suite of market factors and regional characteristics. Our results indicate that an estimate of the economic cost of GLRD ranges from \$29,902 to \$226,405 per ha. Our study reports that vineyard managers experiencing a low GLRD prevalence (between 5 and 10%) can minimize losses by roguing and replanting symptomatic vines, while those encountering higher disease levels, generally above 25%, should consider minimizing its economic impact by pursuing a full vineyard replacement. Most importantly, we find that optimal disease management should be based on the initial prevalence of the disease, price penalty, timing of disease onset relative to vineyard age, and GLRD-induced yield reductions. Vineyard managers should use these management guidelines with caution and tailor them to their unique market opportunities, potential market prices, risk to reputation, and annual operating costs. However, robust results showed that the NPV benefit of roguing and replanting diseased vines and treating insect vectors is often a preferable strategy regardless of the market targeted (from premium to ultra-premium) or production region.

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