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Heterogeneous Benefits of Virus Screening for Grapevines in California

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Abstract:

The economic losses due to GLRaV-3 are substantial and vary significantly across the main regions of the Californian grape sector. We expand the model of Fuller et al. (2018) to accommodate the varied production and market conditions that prevail across the state. We estimate that the total value of virus screening is nearly \$70 million per year outside the North Coast region – for a total value statewide of roughly \$90 million per year. The value of screening varies dramatically by region and grape type and according to other preventative disease management practices with the highest value accruing to table grapes in the South Valley region and white wine grapes in the Central Coast region. We estimate that growers could pay between \$3 and \$12 per vine for virus screening and still breakeven, which is currently higher than the full cost of most vines. Although we do not assess the impact of virus screening on retail prices for table grapes and wine, consumers have almost surely benefited from virus screening as well in the form of lower prices – and will continue to benefit with growers for years to come.

Keywords: Grapevine leafroll, GLRaV-3, virus screening, benefit-cost analysis, disease management, economics.

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Introduction

Viruses and associated crop diseases impose significant costs on growers and consumers despite aggressive disease management and prevention. In the context of grapes, grapevine leafroll viruses are among the most harmful (Rayapati et al. 2014), among which the Grapevine Leafroll associated Virus-3 (GLRaV-3) is particularly problematic anywhere grapes are grown (Almeida et al. 2013, Maree et al. 2013, and Tsai et al. 2008). GLRaV-3 reduces grape yield and quality by decreasing sugar content, changing pigmentation and delaying ripening (Fuller et al. 2018). In California vineyards, the virus spreads primarily by mealybugs (Golino et al. 2002) and can reduce yield by more than 30% in diseased vines (Komar et al. 2010, Moutinho-Pereira et al. 2012, and Walter and Legin 1986).

Due to the lack of effective control strategies for GLRaV-3, growers implement a variety of preventative techniques to mitigate damages from the virus, most notably by planting virus-free vines, and rogueing (removing) infected vines and replacing them with virus-free vines (Fuller et al. 2018). Beginning in 2010, virus screening services, such as those provided by Foundation Plant Services (FPS) at University of California-Davis, set a new and higher screening standard for grapevines and helped to ensure healthy grape rootstock varieties (FPS 2018), albeit at limited capacity. In recent years, screening capacity has rapidly spread to the private sector, where many private nursery companies are now routinely screening all of their rootstock. This dramatically expanded capacity to screen vines for GLRaV-3 raises new questions about how the pronounced heterogeneity across California in grape varieties, production conditions, management practices, and market prices translate into differential benefits to growers from virus screening.

In this paper, we address these questions by assessing the value of screening to grape growers across the very different production regions of California (see Table 1). Specifically, we extend the work of Fuller et al. (2018), which models the economic benefits associated with GLRaV-3 screening of red wine grapes in California’s North Coast region, to consider the impact of heterogeneity in market and production conditions on these benefits. We apply this extended model to the three other major grape-growing regions in California – the Central Coast, the North Coast, and the South Central Valley – and to red wine grapes, white wine grapes and table grapes.¹ To estimate the value of virus screening across these regions and grape varieties, we account for differences in virus expression, growing conditions, yield, and prices between grape varieties and growing regions. Through our use of benefit estimates that explicitly reflect these dimensions of heterogeneity, we aim to better understand how the rapidly expanding virus screening capacity is translating into grower benefits across the diverse California grape sector.

[Table 1: Grape Production in the Central Coast, North Central Valley, and South Central Valley Regions and California]

Methods

Our modelling approach builds on Fuller et al. (2018). In this model, the variable profit of a representative vineyard block simply reflects the grape grower’s profits by subtracting virus-related costs from total revenue:

¹ We intentionally exclude raisins from this expanded model since losses due to GLRaV-3 are much lower for these growers than for other grape growers.

$$\pi_t = R_t - C_t \quad (1)$$

where π_t denotes the variable profit in year t , R_t denotes the total revenue in year t , C_t denotes the virus-related costs in year t .

The grower's revenue depends on grape yields, the price received per ton of grapes, and reductions in production contingent on the presence and impact of the GLRaV-3 virus. The total revenue in year t is calculated as:

$$R_t = b_t PY \left(1 - a \sum_{n=0}^4 (1 - b_n) d_{t-n-1} - s d_t \right) \quad (2)$$

where b_n (or b_t) denotes the yield from vines of a given age, n (or t), as a proportion of yield from mature vines, P represents the price of grapes, Y denotes the yield of mature vines without GLRaV-3, a is the proportion of diseased vines that are identified, rogued and replaced each year, d_t denotes the disease incidence in year t expressed as a proportion of the total number of vines in the field, and s denotes the proportion of yield lost to the virus in diseased vines. In Equation (2), b_t is included to account for the fact that a new vineyard with young vines only gradually ramp up production. The term $a \sum_{n=0}^4 (1 - b_n) d_{t-n-1}$ captures the reduced yield at the field-level due to the replacement of producing (but diseased) vines with young vines that are not yet fully productive.² The final term, $s d_t$, captures the reduced yield caused by diseased vines in year t that have not been rogued and replaced.

The costs in equation (1) include labor, monitoring costs, cost of new vines to replace diseased vines, and the additional cost of using GLRaV-3 screened vines:

$$C_t = d_t v a (r + c) + \delta_t c v + m \quad (3)$$

where v denotes the planting density, r denotes the replacement cost per vine, c denotes the additional cost per vine for using GLRaV-3-screened vines instead of unscreened vines (for unscreened vines $c = 0$), δ is an indicator variable equal to 1 if the grower is using screened vines in year t and 0 otherwise, and m denotes the cost to monitor for leafroll symptoms (e.g., the cost of training employees to identify infected vines, testing grapes, trimming vines, etc.) in order to identify and rogue diseased vines. Thus, we assume that the virus-related costs consist of replacement costs ($d_t v a (r + c)$), initial set up costs ($\delta_t c v$) if using screened vines, and monitoring costs (m). Combining Equation (1) through (3), we construct variable profit as:

$$\pi_t = b_t PY \left(1 - a \sum_{n=0}^4 (1 - b_n) d_{t-n-1} - s d_t \right) - d_t v a (r + c) - \delta_t c v - m \quad (4)$$

Disease incidence in year t , d_t , is modelled as a function of several factors. Specifically, we assume that:

² Vines that were rogued and replaced from year $t - 2$ to t do not bear grapes in year t , while vines that were rogued and replaced from year $t - 4$ to $t - 3$ do not produce at the level of mature vines, which is reflected in the b_n parameter.

$$d_t = d_{t-1}(1 - a + g + d_0 a) + e \quad (5)$$

where d_{t-1} is the disease incidence in the previous year, g is the disease spread rate within the vineyard block, d_0 is the disease incidence in new unscreened vines, and e is the disease spread rate from neighboring vineyard blocks.

An important cost associated with rogueing and replacing vines in this model is the reduced yield in the vineyard block due to replacing mature (albeit diseased) vines that are still bearing fruit with new vines that are not. This yield drag is captured by b_n scaled by the proportion of newly-planted vines, which is given by a . To account for varietal differences in vine maturity and age-specific yield, we adjust b_n according to the University of California Cooperative Extension (UCCE) Cost and Return Studies (UCCE 2013-2018) as follows:

<i>Red wine grapes</i>	<i>White wine grapes</i>	<i>Table grapes</i>
$b_n = \begin{cases} 0 & \text{if } n \leq 2 \\ 0.375 & \text{if } n = 3 \\ 0.75 & \text{if } n = 4 \\ 1 & \text{if } n \geq 5 \end{cases}$	$b_n = \begin{cases} 0 & \text{if } n \leq 2 \\ 0.57 & \text{if } n = 3 \\ 1 & \text{if } n \geq 4 \end{cases}$	$b_n = \begin{cases} 0 & \text{if } n \leq 2 \\ 0.407 & \text{if } n = 3 \\ 0.66 & \text{if } n = 4 \\ 1 & \text{if } n \geq 5 \end{cases}$

Scenarios to Construct Net Present Value of Screening

Having defined variable profits in this model for each year, we assume a discount rate and compute the net present value (NPV) of these profits over the lifespan of the vineyard, which we assume to be 25 years. To address our primary research question, we use the model (Equation 4) to compute the NPV under the four scenarios in Table 2. Fuller et al. (2018) estimate the benefits to growers from using virus-screened rootstock by comparing the NPV of profits between scenario 1 (planting and replanting, after rogueing, using unscreened vines) and scenario 2 (planting and replanting using screened vines). We follow this methodology for red wine grapes. However, extending this model to white wine grapes and table grapes requires a different approach since growers are unable to visually detect the presence of GLRaV-3 in vines and therefore cannot rogue and replace. We therefore compare the NPV of profits between scenario 3 (planting using unscreened vines, no replanting) and scenario 4 (planting using screened vines, no replanting) for white wine and table grapes. To provide a more direct comparison with white wine and table grapes, we also estimate the benefits to red wine grape growers using scenario 3 versus scenario 4.

[Table 2: Scenarios to Construct Net Present Value (NPV) of Screening Red, White and Table Grapevines]

Break-even Screening Cost

Grapevine nurseries are interested in learning the break-even screening costs to farmers of different grape varieties and in different regions for their pricing strategy. If we assume growers are profit maximizing, then growers should only want to use virus-screened rootstock if the benefits from doing so are positive. With this in mind, we perform an additional analysis to determine the break-even screening cost: the value of c at which revenue from using virus-screened vines exactly covers the associated costs. To calculate the break-even screening cost, we set growers' benefits from adopting screened vines to zero. Holding other inputs constant, we can then compute the break-even screening cost c .

Parameters and Assumptions

A summary of our baseline parameter values and assumptions for each region and grape variety studied are presented in Table 3. For comparison, this table also includes the values used by Fuller et al. (2018) in their study of the North Coast region in California.

[Table 3: Parameter Values by Region]

In 2017, growers in the South Central Valley had the highest yield for all grape varieties across the regions we studied with white grape growers in that region reporting an average yield of nearly 45 metric tons per hectare. Growers in the Central Coast received the highest price per metric ton of crushed wine grapes with an average of \$1,677 per ton for red grapes and \$1,284 per ton for white grapes (CDFA, 2018a and 2018b). The South Central Valley is the only region producing a significant amount of table grapes, and we use county crop reports for information on price and yield from the major table-grape-growing counties in this region: Kern, Tulare, Fresno, and King. On average, the price received by table grape farmers comes close to that received for wine grapes in the Central Coast, at \$1,280 per ton (County Crop Reports, 2016).

While we use the reported crush price for wine grapes to estimate the benefits to growers, the benefit from table grapes cannot be estimated directly using the market price due to significant differences in harvest costs between wine and table grapes. Harvest costs for wine grapes only include the cost of picking and hauling the grapes to the winery, while the table grape growers also incur costs from packaging, commissions, sales and marketing fees, storage, assessment, and inspection (UCCE, 2018). To allow for comparison between table and wine grapes, we compute a price net of these additional harvest costs for table grapes as the basis for estimating growers' benefits.

We use values from the UCCE Cost and Return Studies as estimates of the planting density in vines per hectare. Planting density is highest amongst red wine grapes (1,794 vines/ha) followed by white wine grapes (1,537 vines/ha) and table grapes (1,495 vines/ha). Some of the variation in planting density may reflect the high value of land relative to output for red grapes compared to table grapes. A sensitivity analysis found that adjustments to the concentration of vines per acre affects the value of screening per vine, but has little-to-no significant impact on the benefit per hectare to the farmer.³

We retain the assumptions of Fuller et al. (2018) in regards to monitoring costs of \$20 per hectare for red grape varieties, which reflects the cost of training employees to identify visual symptoms from infected vines while they are in the field performing other tasks. However, due to the difficulty of identifying GLRaV-3 symptoms in white and table grapes, most growers of these varieties do not rogue and replace the diseased vines. To reflect this behavior, we set monitoring costs and replanting rate to zero for these grape varieties.

The prevalence of the virus in an area, or in the nursery of a rootstock supplier, will affect a grower's risk of contamination. In the North Coast, Fuller et al. (2018) estimated the disease incidence in unscreened red grape vines from a rootstock supplier is 30% of the field incidence (i.e., 10% in this case).⁴ However, the disease incidence in screened stock from a nursery generally does not vary with local incidence, and remains relatively constant due to the large area one nursery may supply. To reflect this fact, we set disease incidence at 10% for all wine grape

³ Increasing the planting density to as much as 1600 vines per acre resulted in miniscule changes to the value of screening per acre, while significantly impacting the value per vine.

⁴ The authors explain that the often visually recognizable symptoms of GLRaV-3 make growers less furnish nurseries with diseased vines, which leads to a lower virus prevalence in rootstock material than in its field of origin.

varieties, and 20% for table grapes to reflect the largely overlooked and uncontrolled virus population in the latter, resulting in higher baseline virus prevalence in these fields.

We assume the impact of the GLRaV-3 virus on yield depends on the grape variety and the growing climate. It follows that the largest reduction in yield from the virus, estimated at 35%, occurs in the cooler climate of the Central Coast and for red wine grapes, which are particularly sensitive to the virus. However, some of the yield reductions from the virus can be offset by climactic conditions. This is the case for the South Central Valley, where the virus-induced reduction in sugar content may be mitigated or offset by the increase in sugar production from a warmer climate.⁵ To reflect the nonlinear impact of the virus, we allow flexibility in the yield reduction parameter (s) of our model depending on region and grape variety.

The disease spread rate parameter reflects the frequency of the GLRaV-3 virus within a vineyard block and is assumed to be related to the incidence in the previous year in the region. It is a function of disease prevalence, where areas with low field incidence have higher intra-field contamination rates, meaning that the main source of contamination is vines in the same vineyard block. While areas with high field incidence are more prone to cross-block infection, stemming from neighboring blocks. We use a spread rate of 10% for the North and South Central Valley. In the Central Coast, we use a slightly higher rate of 11%, to reflect slightly lower disease incidence rate in the region and thus higher levels of intra-field infection rates (Fuller et al. 2018).⁶

We use the UCCE Cost and Return Studies to estimate the vine replacement costs, which include labor, the cost of the new vines, fertilizer, and other inputs. The cost of screening, in our model, includes costs associated with in-house virus testing of the rootstock, in contrast to Fuller et al. (2018), whose more conservative cost estimate only includes the testing fee.

Results and Discussion

In this section, we present and discuss the key results of our analysis. The pronounced heterogeneity in growing conditions and grape varieties drives a wide range of net present value (NPV) estimates of the value of virus screening and suggests significant differences in benefits to growers in different regions from using screened vines. Furthermore, we show the importance of growers' management practices in shaping the value of virus screening.

Heterogeneous Losses due to Virus Infection

The presence of GLRaV-3 leads to losses in all regions we study, and for all grape varieties. Table 4 shows the magnitude of these losses, assuming diseased vines are rogued and replaced for the first 5 years in the 'replanting' scenario. For all regions and varieties, the losses are naturally highest when unscreened vines are used in the initial planting and diseased vines are not replaced. The smallest losses for each region and variety are seen when investments in these preventative measures are highest. The significant regional heterogeneity between scenarios and the NPV based on comparing these scenarios is clear. The smallest estimated loss on an annual per hectare basis is \$406 for white grapes in the Central Coast region when screened vines are used in initial planting. This is a loss of 6.4 percent of the total value of production. Although this is the smallest loss due to GLRaV-3, it still represents over \$10,000 in discounted losses per hectare over 25 years.

⁵ We thank Neil McRoberts, Associate Professor of Plant Pathology (UC Davis) for this insight.

⁶ Again, confirmed by Neil McRoberts (UC Davis).

[Table 4: Losses from GLRaV-3]

The largest per hectare loss due to the virus is for table grapes in the South Central Valley for unscreened vines. Here, GLRaV-3 is responsible for a loss of \$3,483 annually, or nearly \$90,000 over 25 years. As noted, the yield and price of table grapes are both higher than the averages for wine grapes, which amplifies the economic losses due to the virus. The total value of production for table grapes in the South Central Valley is reduced by 17.5 percent. This result is likely driven by a high virus incidence rate in the South Central Region, coupled with a high tonnage price for table grapes. Among wine grapes the highest loss by magnitude is still significant at \$1,612 per hectare per year for red grapes in the Central Coast with no preventative measures. This result is lower per hectare than Fuller et al. (2018), who estimate losses of \$2,643 per ha for red wine grape growers in the climactically similar North Coast region. However, if we account for a lower tonnage price and a higher yield in the Central Coast region the result is consistent with their findings. This translates to an upper limit estimate loss of over \$40,000 in NPV over 25 years, or a 17.5 percent decrease in total value of production. Red wine grapes in the North Central Valley have a slightly lower annual per hectare loss of \$1,461. However, this accounts for a higher percent of total value of production, at nearly 20 percent.

Aggregated to the regional level, table grapes again show the largest losses due to GLRaV-3: Over \$100 million per year regardless of preventative management practices. Among wine grapes, heterogeneity between scenarios and across regions is pronounced. Red wine grapes in the North Central Valley and Central Coast suffer estimated losses of \$50 million and \$40 million per year respectively. The smallest regional loss is for white grapes in the North Central Valley when screening is used, at \$6.1 million per year.

Farmers can reduce the losses from GLRaV-3 by using preventative measures, including using screened vines in initial planting for all grape varieties and rogue-and-replacing infected red wine vines⁷ with screened vines. We still assume growers do not replace infected white wine grapes or table grapes due to the lack of visual symptoms of infection in these varieties.

Under these preventative measure scenarios (2 and 4 in Table 2), the annual virus-induced losses to growers range from \$406 to \$2,757 per hectare. Even at the smallest estimated loss of \$406 per ha for white grapes in the Central Coast region, we estimate a loss of 6.4 percent of the total value of production, which represents over \$10,000 in discounted losses per hectare over 25 years. The highest losses are incurred by table grape growers at a net present value of \$68,917 per hectare over the 25-year lifespan of the vineyard. This result is driven by the high price for table grapes and the high virus incidence in the region. The South Central Valley is also the region where growers of wine grapes incur the highest losses from GLRaV-3 – at \$27,656 per hectare for red grapes and \$28,339 for white grapes over the lifespan of the vineyard. The virus-induced losses in the South Central Valley are high despite the use of preventative measures in part because growers still face a high risk of contracting the virus from neighboring blocks in this high incidence region.

By employing the preventative measures available to them, all grape growers have the potential of mitigating losses due to the GLRaV-3 virus. Red wine grape growers in the Central Coast have the largest mitigation potential, estimated at \$1,164 per hectare annually, by using screened rootstock on initial planting, coupled with rogueing and replacing infected vines.

⁷ We assume red wine grape growers rogue and replace vines during the first five years after initial planting.

Heterogeneous Benefits of Screened Vines

In the previous section we showed how all regions and grape varieties incur losses from the GLRaV-3 virus, particularly in the absence of preventative measures. Table 5 displays the benefit of screening on a per vine, per hectare, and regional level. It includes a sensitivity analysis for the level of virus incidence in unscreened vines, with the relevant virus incidence level depicted in bold font.

[Table 5: Net Benefits of Screening for Growers]

The benefits of screening new vines for GLRaV-3 vary widely by region and grape type. Table grape growers in the South Central Valley have the highest potential NPV benefit from screening, with a per vine benefit of \$12.14. At the regional level, this high value of screening for table grapes translates into a benefit of nearly \$900 million in NPV over 25 years. Growers of white wine grapes in the Central Coast region also see considerable benefits of screening with the potential NPV benefit from screening at \$11.25 per vine. The regional benefit to table grape growers in the South Central Valley, however, far exceeds the regional benefits to white grape growers in the Central Coast (estimated at \$260 million in NPV over 25 years) due to the size of the table grape industry.

Even for regions with lower relative benefits, the financial gains from screening are significant. For example, while red wine grapes in the South Central Valley have the smallest per vine benefit of \$2.49 per vine over 25 years, this still aggregates to \$4,500 per hectare or \$90 million for the region over 25 years.⁸ None of the NPV estimates are negative, which indicates that the expected economic benefits from screening outweigh the associated costs, including most importantly our assumed cost of screened vines (*c*) of \$0.25/vine. We revisit this assumption below with the break-even screening cost results.

Preventative management practices shape the benefits of screened vines

We assume that growers rogue and replace red vines for the first five years because of the more evident physical manifestation of GLRaV-3 symptoms in red varieties, but do not rogue and replace white or table grapes. This assumption partly explains why the per vine benefit of screening in red grapes is low: When growers have other options at their disposal to help control the virus, the value of screening is lower.

This raises an important tradeoff between preventative measures to manage the virus, which complicates the direct comparison of white and table vines with red grape vines. To

⁸ Estimated benefits of virus screening from this model are consistent if we use varietal-specific parameters instead of generic red wine grape and white wine grape values. Cabernet Sauvignon and Chardonnay are the most prominent varieties of red and white grapes grown in California. In 2017, over 40 thousand hectare of each of the two varieties were grown in the Central Coast, North Central Valley, and South Central Valley combined. Cabernet Sauvignon made up 31%, 24%, and 13% of red grape bearing area in the Central Coast, North Central Valley, and South Central Valley respectively. Meanwhile Chardonnay made up 73%, 54%, and 21% of white grape bearing area in the Central Coast, North Central Valley, and South Central Valley respectively. The benefit of screening for these key varieties is remarkably similar to what we saw for the larger grouping of red, white, or table grapes. The NPV over 25 years of Cabernet Sauvignon is \$2.92, \$2.85 and \$2.48 per vine in Central Coast, North Central Valley and South Central Valley, respectively, while the corresponding value is \$2.73, \$2.54 and \$2.49 for red. The comparable values for Chardonnay are \$11.02, \$4.32 and \$2.46 compared to corresponding white wine values of \$11.25, \$5.17 and \$2.92. Both magnitude and order remain nearly the same, suggesting that the model is not greatly biased due to varieties that are outliers in price or yield.

demonstrate how much this management practice offsets the economic benefits of screening, we can compute the NPV for red grapes without rogueing and replacing, as we do for white and table grapes. Figure 1 shows these benefits to screening. Without rogueing and replacing, red wine grapes in the Central Coast region see the highest benefit from the use of screened vines, at \$14.17 per vine over 25 years, which is greater than the net benefit of screening for table grapes.

[Figure 1]

Both results are important: the results that include rogueing and replacing better reflect reality, since many red grape growers choose to rogue and replace. However, while these preventative management practices lower the benefit to the grower from using screened vines, they do not entirely substitute for screening, as growers benefit from using screened vines even when following a rogue and replace regimen. The results for red vines without rogueing and replacing provide a better estimate of the full potential of virus screening and offer a more direct comparison with the other grape types, for which rogueing and replacing is not an option. Since in practice rogueing and replacing vines is more flexible than we have assumed thus far, we next demonstrate the sensitivity of screening benefits to duration of rogueing and replacing from initial planting.

[Figure 2]

Above we assume that growers who rogue and replace only do so in the first five years. To see how the duration, in years, of rogueing and replacing affects results we run a sensitivity analysis. Specifically, we treat rogueing and replacing as a continuous management practice (i.e., how many years after planting are vines rogued and replaced). Figure 2 illustrates the results of the rogueing and replacing for varying lengths of time for all regions.⁹ A value of 25 indicates implementing rogueing and replacing in every year of the vineyard's lifespan. For red grapes, there is an increase in the benefit from using screened vines with the first year of rogueing and replacing. This is because the rogued vine is replaced with a screened vine, allowing the benefit of the screening technology to come through more than once. As the duration of rogueing and replacing grows longer, the benefit to screening quickly drops. This indicates that a grower reaches a high level of virus control from rogueing and replacing in the first few years of the vineyard, and the incremental advantage to employing the practice for longer is diminishing.¹⁰ A grower with red vines should consider including some rogueing and replacing in their management plan, the practice is most valuable in the first year of the vineyard. For example, the

⁹ We assume growers implement the practice only at the end of the year, a value of 0 for years rogued and replaced indicates no-replanting and a non-zero value indicates replanting diseased vines at the end of the prior year.

¹⁰ After reaching a peak NPV of using screened vines in the first year of the rogueing and replacing diseased vines, the NPV drops until reaching a low in year 3 or 4 of this practice, depending on grape variety and region. By employing a rogue and replace practice, growers are reducing the virus incidence and its impact on yield, but they are also reducing yield by planting immature vines, regardless of whether they replace using screened or unscreened vines. After reaching an initial low, the NPV gradually increases, since the reduction in disease incidence has a larger impact on yield, than the temporary reduction in yield from immature vines. The relationship between the disease incidence, vine maturity, and yield is driven by disease growth rate and non-linearity of our model. No replanting results in the highest disease incidence, regardless of screening, but the use of screened vines in replanting, more heavily disrupts the growth of disease incidence than using unscreened vines.

25-year NPV of screening per vine for red wine grapes in the Central Coast is \$15.45, \$2.73, or \$3.53 per vine when rogueing and replacing for 1, 5, or 25 years respectively. The NPV of screening for red grapes in other regions follows a similar pattern, though the magnitude varies by region and type.

From this we derive three conclusions: First, virus screening generally provides the highest benefit to the grower when the rogue and replace strategy is employed in the first year only. Each additional year of rogueing and replacing reduces the benefit of screening. This reiterates our earlier finding that using multiple prevention practices encroaches on the effectiveness of any one method. Second, the NPV of screening is always positive regardless of the number of years rogueing and replacing. The benefit from screening decreases with a longer rogue and replace time horizon, but is never negative. The net benefit of multiple practices remains better than a single practice in all scenarios investigated. Third, after the first year of rogueing and replacing, there is little benefit of rogueing and replacing for subsequent years. Although the benefit from rogueing and replacing, paired with using screened vines, is positive in all years, the additional benefit to the grower is small after the first year.

The minor difference in benefit between rogueing and replacing for 5 or 25 years is due to the reduction in yield, caused by the virus or by replacing using immature vines, disease growth rate and the life span of the vineyard. The spread of GLRaV-3 within a vineyard is nonlinear, such that the virus initially spreads slowly because of low virus presence, and thus fewer sources of contamination. As more vines become infected, there are more sources of contamination and the rate of transmission accelerates. However, after a point the rates of infection are high, transmission rates slow as it becomes harder for the virus to find uninfected vines to contaminate. If virus rates can be kept sufficiently low, then rates of infection never accelerate to a point that causes significant damage within the lifespan of the vineyard.

In our model we cap infection rates at 75% to simulate the point where new infections are no longer as feasible, and the virus tends to plateau (Fuller et al. 2018). To illustrate how rogueing and replacing dynamics unfold, consider the case of red grapes in the Central Coast region using unscreened vines in planting and replanting. With no rogueing and replacing, infection rates reach 20% by the fifth year, 50% by the thirteenth year, and from there quickly rise to 75% in the seventeenth year. However, when we rogue and replace for 5 years the infection rate in the fifth year is less than 2%, lower than the starting rate of 10% from planting initially with unscreened vines. Infection rates increase after rogueing and replacing stops, but never reach the levels seen without any rogueing and replacing. It takes until the nineteenth year to reach a virus infection rate of 20%. By the end of the 25-year life span of the vineyard the infection rate has only reached 43% due to a slight acceleration in the last years. We see a similar pattern in the North- and South Central Valley.

This result is affected by the lifespan of our vineyards, which we simulate at 25 years. When there is sufficient rogueing and replacing, the infection rate does not accelerate sufficiently by the final year to cause significant damages. However, if we increase the lifespan of the vineyard the disease spread rate would continue to increase and, given enough time, the infection rate would reach the 75% cap in all scenarios.

Break-even screening cost

As a final perspective on the value of screening to growers, we compute the break-even screening cost, which – as described in the methods section – is the screening cost at which the NPV of screened vines in the scenarios above is zero. These break-even costs are depicted in

Figure 3. The high break-even screening cost for table grapes in the South Central Valley, above \$12 per vine, is largely explained by the high value of table grapes in that region, along with an uncontrolled and overlooked virus population. The use of screened vines will reduce disease incidence, and associated yield reductions. The low break-even screening cost of red and white grapes in the South Central Valley is due to the region's high yield and low price, which reduces the benefit of avoided yield reduction, and thus the benefit of screened vines. As noted earlier, the break-even screening cost for red grapes of around \$3 per vine includes planting and replanting using screened compared to unscreened vines, in both scenarios. If we assume farmers do not replant when using unscreened vines the relative benefit from screening would be higher. The break-even screening cost of white wine grapes in the Central Coast and in the North Central Valley is higher than for red wine grapes, because in the absence of rogueing and replacing practices virus screening of white wine vines is more valuable to growers, as it is one of the few virus management tools available to them.

[Figure 3]

Conclusion

The economic losses due to GLRaV-3 are substantial and vary significantly across the main regions of the Californian grape sector. Fuller et al. (2018) propose a variable profits approach to estimating the value of screening new red wine grapevines for the virus in the high value North Coast region. We expand this model to accommodate the extremely varied production and market conditions that prevail for other types of grapes in other regions of the state.

Based on our broader estimates of the value of virus screening to grape growers across California, four noteworthy findings emerge. First, whereas Fuller et al. (2018) estimate the total annual value of virus screening red wine grapevines to be \$20 million in the North Coast region, we estimate that the value of virus screening for the rest of the main grape regions of California to be more than three times higher at nearly \$70 million.

Second, we see pronounced heterogeneity in this value of virus screening by region and grape type. For example, the value of virus screening per vine is roughly four times higher for white wine grapes in the Central Coast region and for table grapes in the Southern Valley region than it is for red wine grapes in the North Coast region.

Third, the overall value of virus screening is generally higher for white wine and table grapes than for red wine grapes because with the latter growers can more readily detect infected vines and rogue and replace them in order to manage the spread of the virus and to reduce their losses. An optimal rogueing-and-replacing strategy for red wine grapes in the Central Coast region, for example, reduces the value of virus screening by seven fold – from \$14 to nearly \$2 per vine.

Finally, we find that very little of the total value of virus screening has accrued to nurseries in the form of higher prices for screened vines. We estimate that growers could pay between \$3 and \$12 per vine for virus screening and still breakeven, which is higher than the current cost of most vines. Since screening has only marginally increased vine prices, growers throughout the state of California have likely reaped the bulk of the significant \$90 million per year total value of virus screening grapevines. Although we do not assess the impact the expanded grape production attributable to virus screening has had on retail prices for table grapes and wine, consumers have almost surely benefited from virus screening as well in the form of

lower prices. Since these benefits will accrue for decades to come as the vineyards planted with virus-screened vines continue to produce, the stream of benefits to both growers and consumers has just begun.

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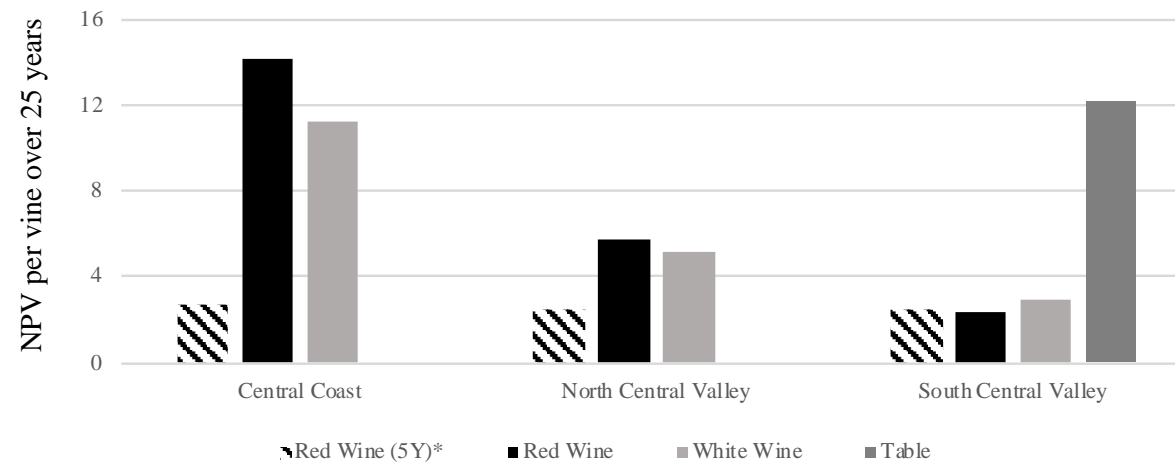
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Figures



* Red vines, if rogued and replaced for five years

Figure 1: NPV per vine over 25 years by region and grape type. The benefit from screening per vine is displayed for each grape variety. For red grapes we display the NPV both using rogue and replace, and without the practice. White and Table grapes are not rogued and replaced.

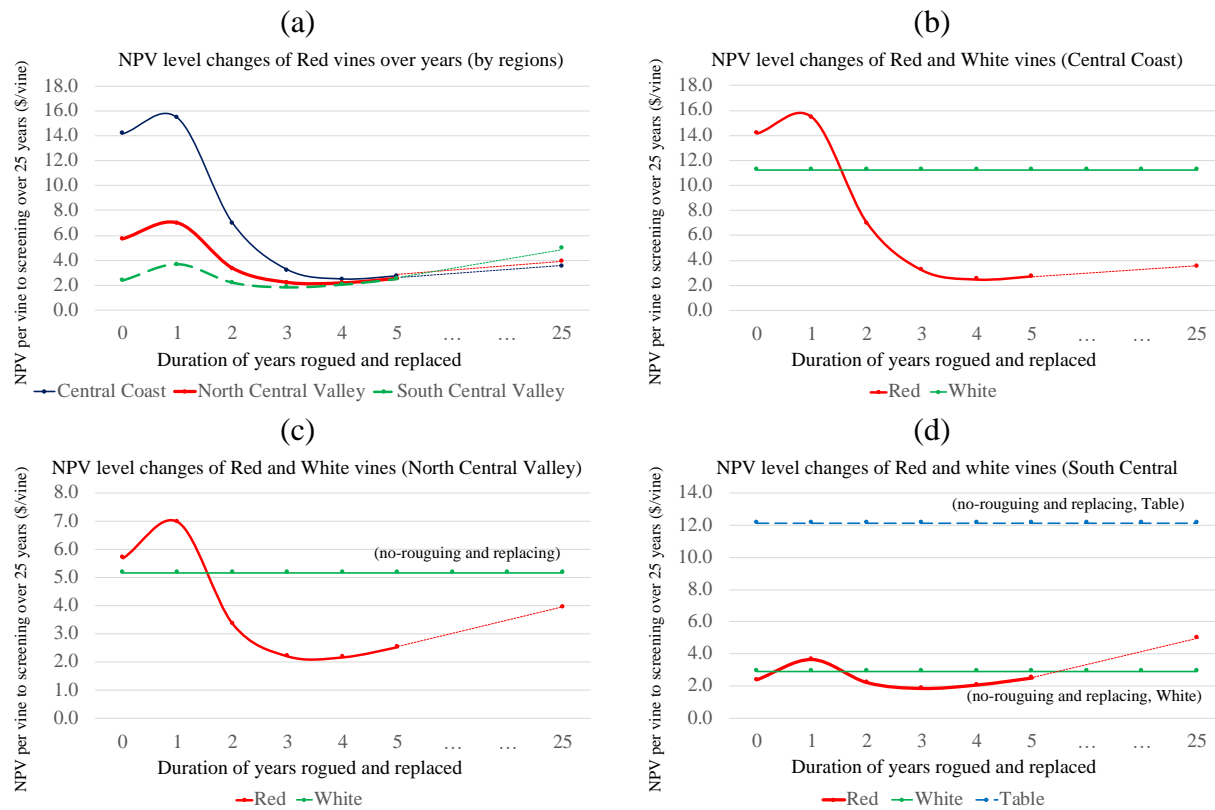


Figure 2: NPV of screened vines, with duration of the rogue and replace practice as continuous variable

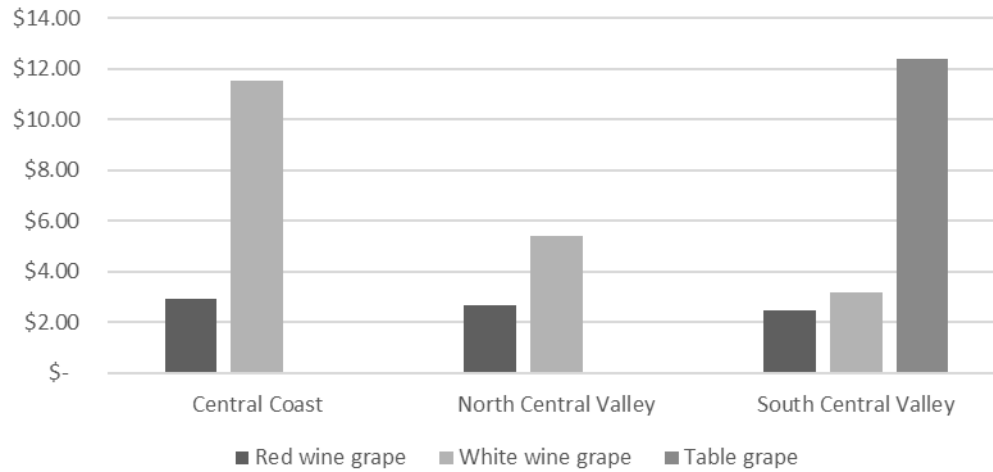


Figure 3: Break-even screening cost for different regions and grape types assuming infected red wine grapes are rogued and replaced for five years after planting.

Tables

Table 1: Grape Production in the Central Coast, North Central Valley, and South Central Valley Regions and California

Production Region and Associated Grape Varieties	Bearing Area, 2017 ^a	Grapes Crushed, 2017 ^b	Yield, 2017 ^b	Average Price, 2017 ^b
	<i>Ha</i>	<i>x 10³t</i>	<i>t/ha</i>	<i>2017\$/t</i>
Central Coast Region (District 6, 7, 8)	40,594	364.5	8.98	1,543.63
Red wine grapes	25,635	240.7	9.39	1,677.13
White wine grapes	14,959	124	8.28	1,284.12
North Central Valley Region (District 9, 10, 11, 12, 17)	54,415	1103.14	20.27	593.87
Red wine grapes	34,385	683.35	19.87	631.19
White wine grapes	20,030	419.79	20.96	533.11
South Central Valley Region (District 13, 14)	85,909	1553.90	40.95	309.48
Red wine grapes	20,013	752.42	37.60	309.30
White wine grapes	17,932	801.48	44.70	309.65
Table grapes ^c	47,964	N/A	26.71	1,279.56
State Total	293,471	3,467	11.81	777.9

^aSource: CDFA/NASS (2018a); ^bSource: CDFA/NASS (2018b); ^cSource all data on table grapes: County Crop Reports (2017); * Does not include Table grapes

Table 2: Scenarios to Construct Net Present Value (NPV) of Screening Red, White and Table Grapevines

	Scenario	Planting	Replanting
NPV(red) <	1	Unscreened	Unscreened
	2	Screened	Screened
NPV(white, table) <	3	Unscreened	No replanting
	4	Screened	No replanting

Table 3: Parameter Values by Region

Parameter	Symbol	Fuller et al. (2018)	Grape	Central Coast	North Central Valley	South Central Valley	Citations
Price (\$/t)	P	\$2,782.00	Red	\$1,677.13	\$631.19	\$309.30	CDFA (2018b)
			White	\$1,284.12	\$533.11	\$309.65	CDFA (2018b)
			Table	N/A	N/A	\$1,279.56	County Crop Reports (2017)
Yield (t/ha)	Y	7.40 t/ha	Red	9.39	19.87	37.58	CDFA (2018a and 2018b)
			White	8.28	20.95	44.7	CDFA (2018a and 2018b)
			Table	N/A	N/A	26.71	County Crop Reports (2017)
Hectares in Region (Bearing Area)	ha	40640 ha	Red	25634.83	34385.36	20013.34	CDFA (2018b)
			White	14958.81	20029.53	17931.64	CDFA (2018b)
			Table	N/A	N/A	47964.36	County Crop Reports (2017)
Diseased vines replanted (%/yr)	a	90%	Red	0% or 90%	0% or 90%	0% or 90%	Fuller et al. (2018), Assumption
			White	0%	0%	0%	
			Table	N/A	N/A	0%	
Yield reduction for diseased vines (%)	s	35%	Red	35%	35%	30%	Atallah et al (2012), Fuller et al. (2018), Neil McRoberts
			White	35%	30%	25%	
			Table	N/A	N/A	25%	
Planting density (vines/ha)	v	3,267 ha	Red	1,794	1,794	1,794	UCCE Cost Studies (2013, 2015, and 2018)
			White	1,537	1,537	1,537	
			Table	N/A	N/A	1,495	
Replacement vine cost (\$/vine)	r	\$14.45	Red	\$14.23	\$14.23	\$14.23	UCCE Cost Studies (2013, 2015, and 2018)
			White	\$14.85	\$14.85	\$14.85	
			Table	N/A	N/A	\$14.60	
	c	0.048	Red	0.25	0.25	0.25	Assumption

Additional cost for GLRaV-3-screened vines (\$/vine)			White	0.25	0.25	0.25	
			Table	N/A	N/A	0.25	
Cost to monitor for leafroll symptoms (\$/ha)	m	\$20/ha	Red	20\$/ha	20\$/ha	20\$/ha	Fuller et al. (2018)
			White	No monitor	No monitor	No monitor	
			Table	N/A	N/A	No monitor	
Disease spread rate (% of last year's <i>d0</i>)	g	10%	Red	11%	10%	10%	Fuller et al. (2018), Neil McRoberts
			White	11%	10%	10%	
			Table	N/A	N/A	10%	
Disease incidence in unscreened vines (%)	dt	10%	Red	10%	10%	10%	Fuller et al. (2018), Assumption
			White	10%	10%	10%	
			Table	N/A	N/A	20%	
Disease entering from other blocks (%/yr)	e	1.50%	Red	0.50%	1.50%	3.00%	Neil McRoberts
			White	0.50%	1.50%	3.00%	
			Table	N/A	N/A	3.00%	
Real discount rate (%/yr)	n/a	3%	Red	3%	3%	3%	Fuller et al. (2018)
			White	3%	3%	3%	
			Table	N/A	N/A	3%	

Table 4: Losses due to GLRaV-3 by scenario ([#]), grapevine type and region

				Average annual discounted losses		Discounted losses over 25 years	
		Planting	Replanting	<i>per ha</i> <i>(\$/ha/year)</i>	<i>Entire region</i> <i>(million\$/year)</i>	<i>per ha</i> <i>(\$/ha)</i>	<i>Entire region</i> <i>(million\$)</i>
Central Coast	Red	[1] Unscreened	Unscreened	644	16.5	16,102	412.8
		[2] Screened	Screened	448	11.5	11,197	287.0
	White	[3] Unscreened	No replanting	1,098	16.4	27,452	410.7
		[4] Screened	No replanting	406	6.1	10,159	152.0
North Central Valley	Red	[1] Unscreened	Unscreened	1,088	37.4	27,206	935.5
		[2] Screened	Screened	906	31.2	22,655	779.0
	White	[3] Unscreened	No replanting	1,126	22.6	28,158	564.0
		[4] Screened	No replanting	808	16.2	20,204	404.7
South Central Valley	Red	[1] Unscreened	Unscreened	1,285	25.7	32,132	643.1
		[2] Screened	Screened	1,106	22.1	27,656	553.5
	White	[3] Unscreened	No replanting	1,313	23.5	32,832	588.7
		[4] Screened	No replanting	1,134	20.3	28,339	508.2
	Table	[3] Unscreened	No replanting	3,483	167.0	87,065	4,176.0
		[4] Screened	No replanting	2,757	132.2	68,917	3,305.5

Table 5: NPV of Screening for Growers

			Average annual discounted value			NPV over 25 years		
		GLRaV-3 incidence in unscreened	<i>per vine</i> (\$/vine/year)	<i>per ha</i> (\$/ha/year)	<i>Entire region</i> (mil\$/year)	<i>per vine</i> (\$/vine)	<i>per ha</i> (\$/ha)	<i>Entire region</i> (mil\$)
Central Coast	Red	5%	0.05	81	2.1	1.13	2,020	51.8
		10%	0.11	196	5.0	2.73	4,904.8	125.7
		30%	0.53	955	24.5	13.30	23,863	611.7
	White	5%	0.28	429	6.4	6.97	10,716	160.3
		10%	0.45	692	10.3	11.25	17,293	258.7
		30%	0.75	1,154	17.3	18.77	28,851	431.6
North Central Valley	Red	5%	0.04	75	2.6	1.04	1,873.8	64.4
		10%	0.10	182	6.3	2.54	4,551.6	156.5
		30%	0.46	817	28.1	11.39	20,427	702.4
	White	5%	0.12	177	3.5	2.88	4,419	88.5
		10%	0.21	318	6.4	5.17	7,954	159.3
		30%	0.40	618	12.4	10.05	15,452	309.5
South Central Valley	Red	5%	0.04	74	1.5	1.02	1,838	36.8
		10%	0.10	179	3.6	2.49	4,475.5	89.6
		30%	0.43	776	15.5	10.81	19,397	388.2
	White	5%	0.06	93	1.7	1.51	2,316	41.5
		10%	0.12	180	3.2	2.92	4,494	80.6
		30%	0.25	377	6.8	6.13	9,417	168.9
	Table	10%	0.30	445	21.3	7.44	11,123	533.5
		20%	0.49	726	34.8	12.14	18,148	870.5
		30%	0.59	887	42.6	14.84	22,185	1,064.1

Red vines are rogued and replaced the first five years, all other vines have no replanting.