Heterogeneous Benefits of Virus Screening for Grapevines in California

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Abstract: The economic losses due to grapevine leafroll-associated virus 3 (GLRaV-3) are substantial and vary significantly across California grape regions. We expand a published economic model designed to estimate the losses associated with GLRaV-3 to accommodate the varied production and market conditions that prevail across these regions. This expanded model provides the basis for assessing the value of screening grapevines for GLRaV-3 across the heterogeneous production conditions that prevail in California, which may have important distributional effects in the industry with implications for producers, consumers, and other stakeholders. We estimate that the total potential value of virus screening statewide is roughly $90 million per year, or 1.6% of the estimated $5.5 billion annual value of production of the California grape industry. Nearly 80% of this accrues to regions outside the high-value North Coast winegrape region. The value of screening varies by region and grape type and according to disease management practices, with the highest value accruing to table grapes in the South Central 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 at establishment, which is higher than the current market price of most vines, and still break even. If nurseries providing screened vines continue to capture only a fraction of this value through higher vine prices, the vast majority will accrue to growers and, ultimately, to consumers through lower retail prices for grapes and wine. The substantial investments in screening capacity in both the private and public sector will likely generate benefits for years to come.

Key words: benefit-cost analysis, disease management, economics, GLRaV-3, grapevine leafroll, virus screening

Viruses and associated crop diseases impose significant costs on growers and by extension, 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 everywhere grapes are grown (Tsai et al. 2008, Almeida et al. 2013, Maree et al. 2013). GLRaV-3 reduces grape yield and quality by decreasing sugar content, changing pigmentation, and delaying ripening (Fuller et al. 2019). In California vineyards, the virus spreads primarily by mealybugs (Golino et al. 2002). Estimates from the literature show yield reductions of 30% or more due to the virus in infected vines (Komar et al. 2010, Moutinho-Pereira et al. 2012).

Due to the lack of effective control strategies for GLRaV-3, growers implement a variety of preventative techniques to mitigate damage from the virus, most notably by striving to plant virus-free vines and rogueing (removing) infected vines for red grapes and replacing them with virus-free vines (Fuller et al. 2019). 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 nurseries now routinely screen all of their rootstock. This drastically expanded capacity to screen vines for GLRaV-3 raises questions about how the pronounced heterogeneity across California in grape varieties, production conditions, management practices, and market prices translates into differential benefits to growers from virus screening. The resulting heterogeneity of screening benefits may have distributional effects in the California grape industry with important implications for growers, grower

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Acknowledgments: The authors thank Kate Fuller, Julian Alston, and Deborah Golino for their assistance and feedback, which made it possible to expand on their earlier work. Neil McRoberts and Olena Sambucci also provided important suggestions and direction, for which the authors are grateful. Two anonymous reviewers raised important questions and offered helpful suggestions for improving and clarifying the analysis and presentation of results. Finally, this work, which started as a case study project with the Wonderful Nurseries, benefited from the insights and expertise of Dustin Hooper, Dylan Keith, Adam Lovgren, Justin Rowe, Brad Kroeker, and Marta Francis as part of that project. The project received modest travel support from the Department of Agricultural and Resource Economics but no other financial research support.

Manuscript submitted May 2019, revised Nov 2019, March 2020, accepted March 2020

doi: 10.5344/ajev.2020.19047

associations, nurseries, other industry stakeholders, and, ultimately, consumers.

In this paper, we address these questions by assessing the value of virus screening to grapegrowers across the very different production regions of California. Table 1 demonstrates how pronounced the prevailing production and market conditions are in these regions. This contributes to the literature on the economics of virus control, especially the value of screening in conjunction with other management practices. The estimates we find are in line with findings from New York (Atallah et al. 2012) and the grape-producing regions of California (Ricketts et al. 2015), as well as a model-based study on optimal control methods (Atallah et al. 2015). We extend the work of Fuller et al. (2019), 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 this pronounced heterogeneity in market and production conditions on these benefits. We apply this extended model to the three other major grapegrowing regions in California—the Central Coast, the North Central Valley, and the South Central Valley—and to red wine grapes, white wine grapes, and table grapes. We aim to estimate the potential value of virus screening across these regions and grape varieties. To capture this heterogeneity, 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. As a recent development in the ever-shifting competitive landscape, virus screening enhances grapegrowers' productivity and profitability in ways that are easily overlooked. This paper sheds light on how, how much, and where these screening innovations and investments benefit the California viticulture industry.

Materials and Methods

Our modeling approach extends the model of Fuller et al. (2019) to accommodate white wine grapes, table grapes, and the three other viticulture regions of California. Using the same structure as the Fuller et al. (2019) model, which we present below, we incorporate new parameters and a wider range of parameter values to reflect the heterogeneity across these grape types and regions (see Table 1). In this model, the variable profit of a representative vineyard block, referred to hereafter as profit, simply reflects the grapegrower's total revenue minus virus-related costs:

$$\pi_t = R_t - C_t \qquad \text{Eq. 1}$$

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

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:

$$R_t = b_t PY\left(1 - a\sum_{n=0}^{4}(1-b_n)d_{t-n-1} - sd_t\right) \qquad \text{Eq. 2}$$

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. The yield loss captured by this s parameter can include both lost production and lost quality due, for example, to virus-induced reductions in sugar content. In Equation 2, b_t is included to account for the fact that a new vineyard with young vines reaches mature yield levels only with time. The term $a\sum_{n=0}^{4}(1-b_n)d_{t-n-1}$

Table 1 Grape production in the Central Coast, North Central Valley, and South Central Valley regions of California.

Production region and associated grape varieties	Bearing area 2017[a] (Ha)	Grapes crushed 2017[b] ($\times 10^3$t)	Yield 2017[b] (t/ha)	Average price 2017[b] (2017$/t)
Central Coast region (District 6, 7, 8)	40,594	364.50	8.98	1543.63
Red wine grapes	25,635	240.70	9.39	1677.13
White wine grapes	14,959	124.0	8.28	1284.12
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	1279.56
State total	293,471	3467	11.81	777.9

[a]Source: (CDFA 2018a).
[b]Source: (CDFA 2018b).
[c]Source: All data on table grapes are from the County Crop Reports (Fresno County 2017, Kern County 2017, Kings County 2017, Madera County 2017, Tulare County 2017).

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. 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, as reflected by the parameter. The final term, sd_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:

$$C_t = d_t va(r + c) + \delta_t cv + m \qquad \text{Eq. 3}$$

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 equal to 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 ($d_t va$ (r +c)), initial setup costs ($\delta_t cv$) if using screened vines, and monitoring costs (*m*) (Fuller et al. 2019). Following Fuller et al. (2019) we combine Equations 1 through 3, and construct profit as:

$$\pi_t = b_t PY\left(1 - a\sum_{n=0}^{4}(1 - b_n)d_{t-n-1} - sd_t\right) - d_t va(r + c) - \delta_t cv - m \qquad \text{Eq. 4}$$

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

$$d_t = d_{t-1}(1 - a + g + d_0 a) + e \qquad \text{Eq. 5}$$

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.

One 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 et al. 2013, 2015, 2016, 2018a, 2018b, 2018c, 2018d) as follows:

Red wine grapes *White wine grapes* *Table grapes*

$$b_n = \begin{cases} 0 \; if \; n \le 2 \\ 0.375 \; if \; n = 3 \\ 0.75 \; if \; n = 4 \\ 1 \; if \; n \ge 5 \end{cases} \qquad b_n = \begin{cases} 0 \; if \; n \le 2 \\ 0.57 \; if \; n = 3 \\ 1 \; if \; n \ge 4 \end{cases} \qquad b_n = \begin{cases} 0 \; if \; n \le 2 \\ 0.407 \; if \; n = 3 \\ 0.66 \; if \; n = 4 \\ 1 \; if \; n \ge 5 \end{cases} \qquad \text{Eq. 6}$$

Scenarios to construct net present value of screening. Having defined 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 (Atallah et al. 2012, Fuller et al. 2019). We use the most recent estimates as the basis for key parameters in the model, which we assume are constant over the vineyard lifespan. To address our primary research question, we use the model (Equation 4) to compute the NPV of profits under the four scenarios in Table 2. Fuller et al. (2019) estimated 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 because growers are unable to visually detect the presence of GLRaV-3 in white variety vines and therefore cannot rogue and replace (Daane et al. 2012, Almeida et al. 2013). Our primary estimates 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 NPV of screening to red wine grape growers using scenario 3 versus scenario 4. Because some table grapes are red varieties, this may be an underestimate of the true use of rogueing and replacing in this category. Thus, for comparison purposes we also generate estimates for a secondary scenario that assumes growers of white wine grapes and table grapes can rogue and replace.

Break-even screening cost. In this paper we also estimate the break-even screening costs to farmers of different grape varieties and in different regions for their pricing strategy. This is the value at which the net benefits to farmers are zero, an estimate that may be of interest to grapevine nurseries in setting prices. If we assume growers are profit maximizing, then growers should want to use virus-screened rootstock only if the net 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' net benefits from adopting screened vines to zero. Holding other inputs constant, we can then compute

Table 2 Primary scenarios used 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*)

the break-even screening cost *c*. By comparing *c* to the virus screening costs that are passed on to growers in the form of higher vine prices, we can shed light on the likely distribution of these benefits to growers and, through competitive market forces, ultimately, consumers.

Parameters and assumptions. A summary of our baseline parameter values and assumptions for each region and grape variety studied is presented in Table 3. For ease of comparison, this table also includes the values used by Fuller et al. (2019) in their study of the North Coast region in California.

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 t/ha. Growers in the Central Coast received the highest price per ton of crushed winegrapes, with an average of $1677 per ton for red grapes and $1284 per ton for white grapes (CDFA 2018a, 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 winegrapes in the Central Coast, at $1280 per ton (Fresno County 2017, Kern County 2017, Kings County 2017, Madera County 2017, Tulare County 2017).

While we use the reported crush price for winegrapes 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 winegrapes include only 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 et al. 2018a, 2018b, 2018c, 2018d). 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 among red wine grapes (1794 vines/ha) followed by white wine grapes (1537 vines/ha) and table grapes (1495 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 reveals that adjustments to the concentration of vines per hectare affect the benefit of screening per vine, but have little to no impact on the benefit per hectare to the farmer: Increasing the planting density to as much as 3950 vines/ha results in miniscule changes to the value of screening per hectare, while significantly impacting the value per vine.

We retain the assumptions of Fuller et al. (2019) in regards to monitoring costs of $20/ha 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 (white) 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. (2019) 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), explaining that the often visually recognizable symptoms of GLRaV-3 make growers less likely to furnish nurseries with diseased vines, which leads to a lower virus prevalence in rootstock material than in its field of origin. 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 winegrape varieties, and at 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 also conduct sensitivity analysis of disease incidence at 5 and 30% for all winegrapes and at 10 and 30% for table grapes.

We assume the impact of the GLRaV-3 virus on yield depends on the grape variety and the growing climate (Daane et al. 2012, Almeida et al. 2013). 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 climatic 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 (Neil McRoberts, personal communication). To reflect the diverse impact of the virus, we allow flexibility in the yield reduction parameter (s) of our model depending on region and grape variety.

The disease incidence parameter reflects the incidence of the GLRaV-3 virus in the current year 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 (Fuller et al. 2019). 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 (Neil McRoberts, personal communication).

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. (2019), whose cost estimate includes only 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

Table 3 Parameter values by region and grape variety.[a]

Parameter / corresponding symbol / grape	Fuller et al. (2019)	Central Coast	North Central Valley	South Central Valley	Citations
Price ($/t) / P					
Red	$2782.00	$1677.13	$631.19	$309.30	CDFA (2018b)
White		$1284.12	$533.11	$309.65	CDFA (2018b)
Table		N/A	N/A	$1279.56	County Crop Reports (2016)
Yield (t/ha) / Y					
Red	7.40 t/ha	9.39	19.87	37.58	CDFA (2018a and 2018b)
White		8.28	20.95	44.7	CDFA (2018a and 2018b)
Table		N/A	N/A	26.71	County Crop Reports (2016)
Hectares in region (bearing area) / ha					
Red	40,640 ha	25,634.83	34,385.36	20,013.34	CDFA (2018b)
White		14,958.81	20,029.53	17,931.64	CDFA (2018b)
Table		N/A	N/A	47,964.36	County Crop Reports (2016)
Diseased vines replanted (%/yr) / a					
Red	90%	0% or 90%	0% or 90%	0% or 90%	Fuller et al. (2019), Assumption
White		0%	0%	0%	
Table		N/A	N/A	0%	
Yield reduction for diseased vines (%) / s					
Red	35%	35%	35%	30%	Atallah et al (2012), Fuller et al. (2019), Neil McRoberts (personal communication)
White		35%	30%	25%	
Table		N/A	N/A	25%	
Planting density (vines/ha) / v					
Red	3267 ha	1794	1794	1794	UCCE Cost Studies (2013, 2015, and 2018)
White		1537	1537	1537	
Table		N/A	N/A	1495	
Replacement vine cost ($/vine) / r					
Red	$14.45	$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	$14.60	
Additional cost for GLRaV-3 screened vines ($/vine) / c					
Red	0.048	0.25	0.25	0.25	Personal communication with nursery technicians
White		0.25	0.25	0.25	
Table		N/A	N/A	0.25	
Cost to monitor for leafroll symptoms ($/ha) / m					
Red	$20/ha	$20/ha	$20/ha	$20/ha	Fuller et al. (2019)
White		No monitor	No monitor	No monitor	
Table		N/A	N/A	No monitor	
Disease spread rate (% of last year's d_0) / g					
Red	10%	11%	10%	10%	Fuller et al. (2019), Neil McRoberts (personal communication)
White		11%	10%	10%	
Table		N/A	N/A	10%	
Disease incidence in unscreened vines (%) / d_0					
Red	10%	10%	10%	10%	Fuller et al. (2019), Assumption
White		10%	10%	10%	
Table		N/A	N/A	20%	
Disease entering from other blocks (%/yr) / e					
Red	1.50%	0.50%	1.50%	3.00%	Neil McRoberts (personal communication)
White		0.50%	1.50%	3.00%	
Table		N/A	N/A	3.00%	
Real discount rate (%/yr) / n/a					
Red	3%	3%	3%	3%	Fuller et al. (2019)
White		3%	3%	3%	
Table		N/A	N/A	3%	

[a]All dollar-denominated parameters are drawn from the most recent year available. Because these fall within a five-year window during a period with low inflation, we keep these as nominal values. Monetary estimates from the model are therefore in current (2013-2018) dollars.

and grape varieties generates a wide range of 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 by evaluating how the value of screening changes when used with rogueing and replacing. To complete and compare our analysis conceptually, we present the results from an additional scenario of rogueing and replacing for white and table grapes in Table 4.

Heterogeneous losses due to virus infection. The presence of GLRaV-3 leads to losses in all regions we study, and for all grape varieties. The loss for a given scenario is calculated as the difference in profit with and without any virus-induced losses. Table 4 shows the magnitude of these losses for the primary scenarios where replanting with either unscreened or screened vines is possible only when growers can rogue and replace diseased vines in the first five years after initial planting. 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 of screening 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, in which the yield/hectare and number of hectares is smaller than other regions, when screened vines are used in initial planting. Although this is the smallest loss due to GLRaV-3, it still represents over $10,000 in discounted losses per hectare over 25 years, or 6.4% of the total value of virus-free production.

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 $3483/ha annually, or nearly $90,000/ha over 25 years. As noted, the yield and price of table grapes are both higher than the averages for winegrapes, which amplify the economic losses due to the virus. The total gross value of production for table grapes in the South Central Valley is reduced by 17.5% from a scenario without any virus-induced losses. This result is likely driven by a high disease incidence rate in the South Central Region, coupled with a high tonnage price for table grapes relative to other grape varieties. Among winegrapes, the highest loss by magnitude is still significant at $1313/ha/year for white grapes in the South Central Valley with no preventative measures. This result is lower per hectare than that found by Fuller et al. (2019), who estimated losses of $2643/ha/year for red wine grape growers in the climatically similar North Coast region. However, if we account for a lower tonnage price and a higher yield for white grapes in the South Central Valley region, the result is consistent with their findings. This translates to an upper limit estimate loss of over $30,000/ha in NPV over 25 years, or a 15.8% decrease in total value of production. The highest calculated loss for red wine grapes is $1285 in the South Central Valley when screening is not used, which accounts for 18.9% of the value of production of red wine grapes in this region.

Even when initially planting screened vines (scenarios 2 and 4 in Table 2), the annual virus-induced losses to growers range from $406 to $2757/ha/year. The smallest estimated loss of $406/ha/year for white grapes in the Central Coast region is discussed above. The highest losses with preventative measures are incurred by table grape growers, with an NPV of $68,917/ha over the 25-year lifespan of the vineyard. This

Table 4 Losses due to GLRaV-3 by scenario ([#]), grape type, and region. Results assume rogueing and replacing for five years for red vines, and no rogueing and replacing for white and table vines. For comparison, for white and table vines, we provide results in { } assuming rogueing and replacing.

	Planting	Replanting	Average annual discounted losses: *per ha ($/ha/year)*	Average annual discounted losses: *Entire region (million$/year)*	Discounted losses over 25 years: *per ha ($/ha)*	Discounted losses over 25 years: *Entire region (million$)*
Central Coast						
Red	[1] Unscreened	Unscreened	644	16.5	16,102	413
	[2] Screened	Screened	448	11.5	11,197	287
White	[3] Unscreened	- {Unscreened}	1098 {480}	16.4 {7.2}	27,452 {11,997}	411 {180}
	[4] Screened	- {Screened}	406 {310}	6.1 {4.6}	10,159 {7753}	152 {116}
North Central Valley						
Red	[1] Unscreened	Unscreened	1088	37.4	27,206	936
	[2] Screened	Screened	906	31.2	22,655	779
White	[3] Unscreened	- {Unscreened}	1126 {883}	22.6 {17.7}	28,158 {22,079}	564 {442}
	[4] Screened	- {Screened}	808 {709}	16.2 {14.2}	20,204 {17,731}	405 {355}
South Central Valley						
Red	[1] Unscreened	Unscreened	1285	25.7	32,132	643
	[2] Screened	Screened	1106	22.1	27,656	554
White	[3] Unscreened	- {Unscreened}	1313 {1300}	23.5 {23.3}	32,832 {32,489}	589 {583}
	[4] Screened	- {Screened}	1134 {1106}	20.3 {19.8}	28,339 {27,661}	508 {496}
Table	[3] Unscreened	- {Unscreened}	3483 {3133}	167 {150}	87,065 {78,336}	4176 {3757}
	[4] Screened	- {Screened}	2757 {2488}	132 {119}	68,917 {62,209}	3306 {2984}

result is driven by the high price for table grapes as compared to other vines and the high disease incidence in the region as compared to other regions. The South Central Valley is also the region where growers of winegrapes incur the highest losses from GLRaV-3—$27,656/ha 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.

Table 4 also reports estimated losses for secondary scenarios that assume white wine grape and table grape growers can rogue and replace diseased vines like their red wine grape counterparts. For red table grapes, it is possible to rogue and replace, which reduces the losses due to the virus, so these secondary scenario estimates provide a realistic lower bound on disease losses. While this is a hypothetical scenario for white wine grape growers, these estimates indicate to what extent screening substitutes for rogueing and replacing as a virus management practice. The secondary scenario estimates in Table 4 suggest that rogueing and replacing reduces annual losses by ~56% for white wine grape growers in the Central Coast when planting unscreened vines (e.g., $1098/ha/year to $480/ha/year), but reduces losses by only 25% when growers planted screened vines (e.g., $406/ha/year to $310/ha/year).

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 disease incidence in unscreened vines.

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 per vine from screening at $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 from screening at $11.25/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 NPV of screening per vine of $2.49 over 25 years, this still aggregates to $4500/ha, or $90 million for the region over 25 years.

Table 5 Net present value (NPV) of screening for growers.[a]

Area/grape	GLRaV-3 incidence in unscreened (%)	Average annual discounted value			NPV over 25 years		
		per vine ($/vine/year)	*per ha ($/ha/year)*	*Entire region (mil$/year)*	*per vine ($/vine)*	*per ha ($/ha)*	*Entire region (mil$)*
Central Coast							
Red	5	0.05	81	2.1	1.13	2020.0	51.8
	10	0.11	196	5.0	2.73	4904.8	125.7
	30	0.53	955	24.5	13.30	23,863.0	611.7
White	5	0.28	429	6.4	6.97	10,716.0	160.3
	10	0.45	692	10.3	11.25	17,293.0	258.7
	30	0.75	1154	17.3	18.77	28,851.0	431.6
North Central Valley							
Red	5	0.04	75	2.6	1.04	1873.8	64.4
	10	0.10	182	6.3	2.54	4551.6	156.5
	30	0.46	817	28.1	11.39	20,427.0	702.4
White	5	0.12	177	3.5	2.88	4419.0	88.5
	10	0.21	318	6.4	5.17	7954.0	159.3
	30	0.40	618	12.4	10.05	15,452.0	309.5
South Central Valley							
Red	5	0.04	74	1.5	1.02	1838.0	36.8
	10	0.10	179	3.6	2.49	4475.5	89.6
	30	0.43	776	15.5	10.81	19,397.0	388.2
White	5	0.06	93	1.7	1.51	2316.0	41.5
	10	0.12	180	3.2	2.92	4494.0	80.6
	30	0.25	377	6.8	6.13	9417.0	168.9
Table	10	0.30	445	21.3	7.44	11,123.0	533.5
	20	0.49	726	34.8	12.14	18,148.0	870.5
	30	0.59	887	42.6	14.84	22,185.0	1064.1

[a]Red vines are rogued and replaced the first five years; all other vines have no replanting.

Both magnitude and order remain approximately equal if we use varietal-specific parameters instead of the aggregated red wine grape and white wine grape values used above. Cabernet Sauvignon and Chardonnay are the most prominent varieties of red and white grapes grown in California. In 2017, over 40,000 ha of each of the two varieties were grown in the Central Coast, North Central Valley, and South Central Valley combined (CDFA 2018b). 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. 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 of screening over 25 years of Cabernet Sauvignon is $2.92, $2.85, and $2.48/vine in the Central Coast, North Central Valley, and South Central Valley, respectively, compared to the corresponding values of $2.73, $2.54, and $2.49 across red wine grapes from our model. The values for Chardonnay are $11.02, $4.32, and $2.46 compared to cross-white wine grape values of $11.25, $5.17, and $2.92.

Furthermore, none of the NPV of screening estimates are negative, which indicates that the expected economic benefits from screening outweigh the associated costs, including our assumed cost of screened vines (*c*) of $0.25/vine. We revisit this assumption below with the break-even screening cost analysis.

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 in part explains why the per vine benefit of screening in white and table grapes is higher than in red grapes: when growers employ rogueing and replacing, there is less virus-induced loss left for the screening technology to prevent, leading to a lower benefit from screening technology. When growers have other options at their disposal to help control the virus, the value of screening is at times lower.

This raises an important tradeoff between different preventative measures to manage the virus, which complicates the direct comparison of white and table vines with red grape vines. To further explore this tradeoff and demonstrate how much this management practice offsets the economic benefits of screening, we can compute the NPV of screening 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 NPV from the use of screened vines, at $14.17/vine over 25 years, which is greater than the benefit of screening for table grapes.

The results that include rogueing and replacing better reflect reality because many red grape growers do this as a standard management practice. However, while these preventative management practices lower the marginal 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 an estimate of the full potential of virus screening and offer a more direct comparison with white grape types, for which rogueing and replacing is not an option. Because 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.

Above, we assume that growers who rogue and replace only do so in the first five years. In reality, the number of years a grower chooses to rogue and replace may be higher or lower. 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. We assume growers implement the practice only at the end of the year. A value of 0, for years rogued and replaced, represents no replanting, a non-zero value indicates diseased vines were rogued and replanted at the end of the prior year, and a value of 25 indicates that the practice was implemented in every year of the vineyard's lifespan.

The benefit of screening for each year of rogueing and replacing reflects the diffusion dynamics of the virus. The spread of GLRaV-3 within a vineyard is slow initially 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. After a saturation point, transmission rates slow again as it becomes harder for the virus to find uninfected vines to contaminate (Neil McRoberts, personal communication). 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 the 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. 2019). 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

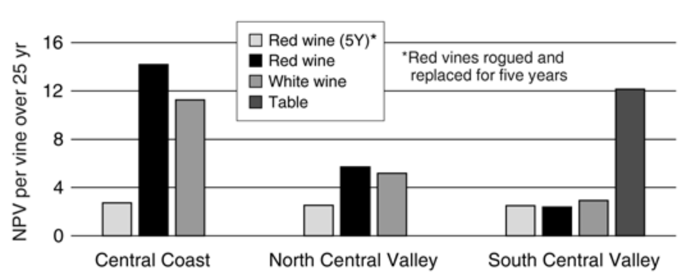

Figure 1 Net present value (NPV) per vine over 25 years by region and grape type. (5Y)* indicates that growers rogue and replace for the first five years, and is modeled only for red wine grapes due to complications identifying the virus in other varieties. All other estimates assume no rogueing and replacing.

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 five 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 reached only 43% due to a slight acceleration in the last years. We see a similar pattern in the North and South Central Valleys.

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 damage. 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.

We draw two key results from Figure 2. First, for red grapes, the highest marginal benefit from screening occurs with one year of rogueing and replacing. As the duration of rogueing and replacing grows longer, the marginal benefit of 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 in subsequent years there is less virus-induced loss for the screening technology to prevent, leading to a lower benefit from screening. Note that this does not mean that the highest profit is achieved with one year of rogueing and replacing, but rather that the highest contribution of screening to profit is achieved with one year of rogueing and replacing.

Second, the marginal benefit of screening is always positive. For example, the 25-year NPV of screening per vine for red wine grapes in the Central Coast is $15.45, $2.73, or $3.53/vine when rogueing and replacing for one, five, or 25 years, respectively (see Figure 2B). The NPV of screening for red grapes in other regions follows a similar pattern, though the magnitude varies by region and type. Even though the benefit of screening decreases after the first year, it remains positive. This means that growers can derive benefit from screening on

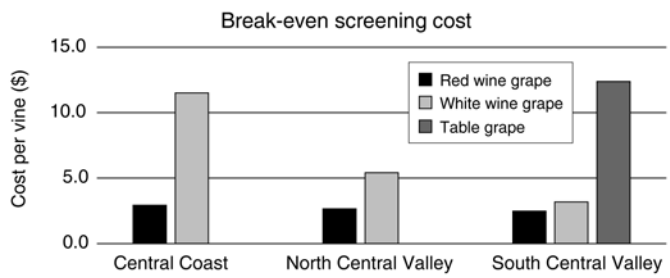

Figure 3 Break-even screening cost per vine (i.e., the largest premium a grower should be willing to pay for screened vines relative to unscreened vines) by region and grape type assuming infected red wine grapes are rogued and replaced for five years after planting.

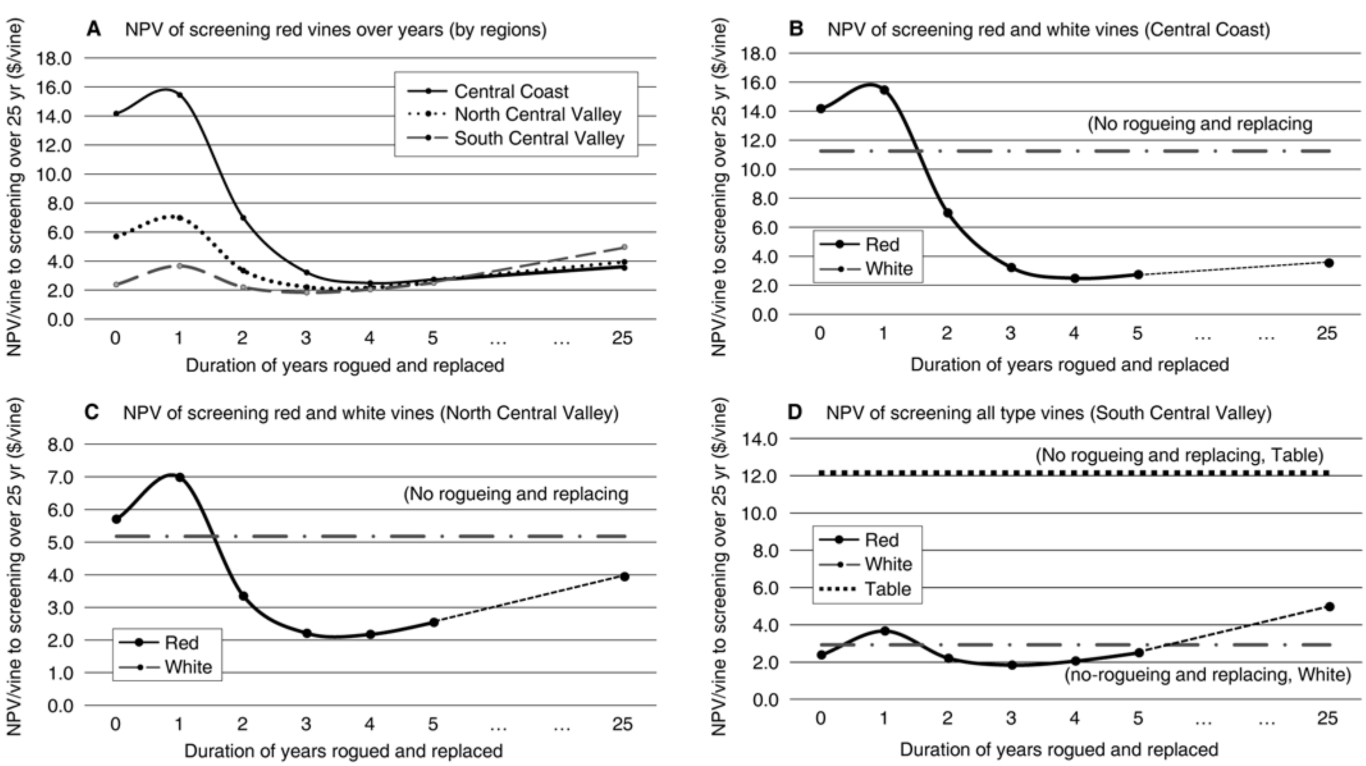

Figure 2 Net present value (NPV) benefit of screening, with duration of the rogue and replace practice as continuous variable. Panel (**A**) shows the NPV benefit of screening for red vines in all regions. Panels (**B**), (**C**), and (**D**) show the NPV benefit of screening for vines in the Central Coast, North Central Valley, and South Central Valley, respectively. Horizontal lines in (**B**), (**C**), and (**D**) indicate NPV of screening with no rogueing and replacing for white grapes and table grapes.

top of rogueing and replacing when rogueing and replacing into the subsequent years.

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 Materials and 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/vine, is largely explained by the high value of table grapes in that region, along with an uncontrolled 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 low price, which reduces the benefit of avoided yield reduction, and thus the net benefit of screened vines. As noted earlier, the break-even screening cost for red grapes of around $3/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.

Conclusion

The economic losses due to GLRaV-3 are substantial and vary significantly across the main regions of the California grape sector. Fuller et al. (2019) proposed 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 grapegrowers across California, four noteworthy findings and implications emerge. First, whereas Fuller et al. (2019) estimated the total annual value of virus screening red wine grapevines to be $20 million in the North Coast region, we estimate the gross potential 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. Combined, the total potential value of screening of $90 million/year represents ~1.6% of the estimated $5.5 billion value of grape production in the state (Alston et al. 2018). Given that this accrues each year to a competitive industry faced with increasing labor costs and tightening profit margins, even a modest gain of this magnitude is economically nontrivial.

Second, we see pronounced heterogeneity in this value of virus screening by region and grape type. For example, the gross 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 South Central Valley region than it is for red wine grapes in the North Coast region.

Third, the NPV 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 NPV of virus screening seven-fold—from $14 to nearly $2/vine.

Finally, these results raise a natural question: Who reaps these significant per vine virus screening benefits? When an innovation—virus screening in this case—generates substantial benefits in a competitive industry, it can have important distributional effects among producers, consumers, and other stakeholders. While fully addressing this question is beyond the scope of this analysis, we offer a few reflections. Although not all new vines are currently virus screened, the largest nurseries routinely screen, and it is likely that growers will come to expect this of the vines they purchase, so the scenario of complete virus screening of new vines may soon be reality. Even before complete virus screening is achieved, our per-vine estimates provide a basis for considering the distribution of screening benefits. Private nurseries can capture a share of these benefits by charging a premium for screened vines, but so far these price premiums have been small compared to our value estimates, suggesting that the majority of the benefits are not accruing to the nurseries providing screening services. Growers then are the natural beneficiaries. We estimate that growers could pay between $3 and $12/vine for virus screening and still break even. Because they are paying less than this as a screened rootstock premium (likely less than $1/vine; Wonderful Nurseries, personal communication), grapegrowers throughout the state of California may have reaped the majority of the virus screening benefits to date. If this benefit distribution holds once all new vines sold in the state are screened, growers may receive a considerable share of the potential $90 million annual total value of virus screening for grapevines.

Of course, once screened vines have diffused across the entire viticulture industry, there will surely be other market-level effects. Ultimately then, consumers may capture a portion of these benefits in the form of lower retail prices for table grapes and wine due to lower production costs attributable to virus screening. Although an assessment of the effect of virus screening on retail prices is beyond the scope of this paper, consumers will likely benefit from virus screening as well through this channel. Indeed, once market prices adjust, they may become the primary beneficiaries. Because the benefits will accrue for decades to come as the vineyards planted with virus-screened vines continue to produce, and as the installed screening capacity continues to supply growers with clean grapevines, the stream of benefits to growers, and ultimately consumers, has just begun.

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