Economic Benefits from Virus Screening: A Case Study of Grapevine Leafroll in the North Coast of California

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Abstract: Viruses and related pathogens have no cure and impose high costs on nurseries and specialty crop producers. These diseases are typically spread through infected planting stock and plant propagation material. For some viruses, field spread after planting is also important in determining vineyard health. However, virus spread can be minimized if clean stock is planted. This paper presents the costs and benefits of a virus screening program for Grapevine Leafroll associated Virus-3 (GLRaV-3) in the North Coast region of California. Grower costs and benefits from using GLRaV-3-free vines were computed and extrapolated to the North Coast winegrape industry as a whole. Economic benefits from the GLRaV-3 testing, therapy, and distribution programs were in excess of \$20 million/yr for the region and substantially outweighed the costs. The results showed potential benefits from removing and replacing diseased vines, rather than leaving them in the vineyard where they can be foci for disease spread. Significant costs were also associated with disease entering from infected vines on neighboring properties.

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

Viruses comprise a class of plant pathogens for which no effective control is available to crop growers other than destruction of the virus-infected plants. If not controlled, these plant pathogens cause various crop diseases that cost growers and consumers billions of dollars annually. Sixty-five different grapevine viruses have been identified (Martelli 2014), a number that is growing rapidly as next-generation sequencing improves detection of unique viruses (Al Rwahnih et al. 2009, Massart et al. 2014). Grapevine leafroll viruses are among the most serious grape pathogens (Rayapati et al. 2014) and have been identified by the American Vineyard Foundation as one of the industry's top five research priorities (see http://avf.org/results). Ten grapevine leafroll-associated viruses have been characterized, of which Grapevine Leafroll associated Virus-3 (GLRaV-3) is regarded as the most important worldwide (e.g., Tsai et al. 2008, Almeida et al. 2013, Maree et al. 2013). Expression of GLRaV-3 virus in vineyards varies across genetic variants of the virus and also across grape cultivars and varieties. GLRaV-3 reduces production and fruit quality by decreasing pigmentation, reducing sugar content, and delaying maturity. Yield reductions of 30% or more in diseased vines have been reported (Walter and Legin 1986, Komar et al. 2010, Moutinho-Pereira et al. 2012).

Grapevine leafroll diseases are vectored mainly by mealybugs, which are common in California vineyards (Golino et al. 2002). Although some authors have proposed that using insecticides to control mealybug populations can help suppress GLRaV-3 incidence (Rayapati et al. 2014), the more effective insecticides are systemic, meaning insects must feed on the vines in order to be killed. This means that insects can enter a vineyard, feed on vines, and transmit the virus before the insecticide takes effect (Almeida et al. 2013). The most effective available management tool is to plant with GLRaV-3-free rootstock and scion materials and to remove (rogue) symptomatic vines and replant with GLRaV-3-free vines. Growers often use a combination of these control strategies to control viral disease (Daane et al. 2012, Almeida et al. 2013).

Several grapevine clean plant centers have been established throughout the United States to provide virus-screened plants to nurseries and growers. Since funding was provided in the 2008 Farm Bill, these centers have worked in partnership with the U.S. Department of Agriculture (USDA) and its National Clean Plant Network to provide a large inventory of plants that are free from a wide variety of pathogenic viruses to

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commercial United States nurseries that produce stock for grapegrowers, among others. In California, the clean plant center responsible for grapevine virus testing, therapy, and distribution is Foundation Plant Services (FPS) at the University of California, Davis. In this paper, the benefits from public investments in the FPS GLRaV-3 screening program are estimated at >$22 million/yr for the North Coast region alone.

Previous economic studies. To the authors' knowledge, no previous studies evaluated the benefits of screening for GLRaV-3 or other leafroll viruses. However, several studies have estimated the economic impact of leafroll and leafroll management. Data from a Cabernet franc vineyard in the Finger Lakes region of New York showed that if no control measures were implemented, the cost of GLRaV-3 infection ranged from $25,407/ha with 30% yield loss and no quality penalty to $41,000/ha with 50% yield loss and a 10% quality penalty. It was also reported that planting GLRaV-3-screened vines initially, rather than unscreened vines, was financially beneficial over a 25-year horizon, even if GLRaV-3-screened vines cost 25% more than unscreened vines (Atallah et al. 2012). Net present valued estimates of losses in California vineyards ranged from $29,902 to $226,405/ha over 25 years in the absence of control. Alternative management strategies for a range of scenarios were also examined. Optimal management depended on the year of disease onset and the region in which the vineyard was located. The optimal strategy for leafroll management in Napa and Sonoma counties was either roguing and replanting with vector control, or replacement of the entire vineyard (Ricketts et al. 2015).

This paper extends previous work by estimating GLRaV-3 losses in California and placing a value on the publicly funded GLRaV-3 screening program in California and on grower benefits from planting virus-screened vines.

Materials and Methods

Model. Winegrape yields, prices, and growing practices vary dramatically across California, as do virus expression and incidence in vineyards. Table 1 gives information on the area planted, yield, and price of winegrapes for counties in the North Coast as well as California as a whole. The model used here is focused on the North Coast region, where growers are acutely concerned about leafroll virus diseases and their spread (Golino et al. 2008). Growers and vintners in the Rutherford area of Napa County in the North Coast have formed neighborhood groups to cooperatively monitor and control both the virus and its vectors. The severity of leafroll disease is affected by the species and strain of the virus, rootstock and scion variety, vineyard management, and environmental considerations, including location (Massart et al. 2014).

Table 1 Winegrape production in the North Coast Region and California.

Production region and associated districts	Bearing area, 2010[a] (Ha)	Grapes crushed, 2010[b] (x $10^3 t_m$)	Yield/ha, 2010[b] (t_m/ha)	Average price, 2010[b] ($/$t_m$)
North Coast region	40,640	300	7.40	2782
Napa (District 3)	22,520	174	7.73	2216
Sonoma and Marin (District 4)	18,121	126	6.95	3567
State total	184,908	3256	17.60	742

[a]CDFA/NASS 2011a.
[b]CDFA/NASS 2011b.

GLRaV-3 was chosen for this analysis because of its severe effects on Cabernet Sauvignon, the predominant variety grown in the North Coast region (Golino et al. 2008). Additionally, GLRaV-3 strains represent the majority of leafroll virus types found in the North Coast region (Sharma et al. 2011). The losses incurred by winegrape growers as a result of GLRaV-3 and the benefits from using GLRaV-3-screened vines were estimated based on measures of "variable profits," defined in this paper as gross revenue minus virus-related costs for a representative hectare of winegrapes. Virus-related costs include the costs of labor and materials required for roguing and replacing diseased vines (including the cost of the replacement vine), any price premium for GLRaV-3-screened vines, production loss from reduced yield of diseased vines, and loss of production during the time when replaced vines are not yet bearing. The remaining "profit" has to cover overhead costs, including capital recovery (depreciation), maintenance, property taxes, and cultural costs not related to leafroll, such as pruning, fertilizer application, and irrigation. Note that this specification presumes all relevant costs are incurred on a per hectare basis and do not vary with yield changes of the sizes being modeled.

Equation 1 describes variable profit for a representative hectare in this region, t years after planting, where t ranges from 0 to 24 years.

$$\pi_t = b_t PY\left(1 - a\sum_{n=0}^{5}(1-b_n)d_{t-n-1} - sd_t\right) - d_t va(r+c) - \delta_t cv - m \quad \text{(Eq. 1)}$$

Variable profit, π_t, is a function of:

- b_n, the yield from vines of a given age, n, as a proportion of yield from mature vines;
- P, the crush price/t_m of winegrapes;
- Y, the yield of mature vines without GLRaV-3, in t_m/bearing hectare;
- a, the proportion of diseased vines identified and replaced each year;
- d_t, the disease incidence in year t, expressed as a proportion of the total number of vines in the hectare;
- s, the proportion of yield lost from disease in diseased vines;
- v, the planting density, in vines/ha;
- r, the replacement cost in $/vine;
- c, the additional cost in $/vine for GLRaV-3-screened vines over unscreened vines (if vines were unscreened, $c = 0$);
- δ, an indicator variable that is 1 if $t = 0$, and 0 otherwise. If growers planted their vineyard in GLRaV-3-screened vines initially, they paid the premium in $t = 0$; and
- m, the cost/ha to monitor for leafroll symptoms (if no monitoring took place, $m = 0$).

In year t, vines that were rogued and replaced in years t through t–2 do not produce, and vines that were rogued and replaced in years t–3 and t–4 do not bear at full capacity, so they bring in proportionally reduced revenue in the amount of

$$a\sum_{n=0}^{5}(1-b_n)d_{t-n-1},$$

and vines that are diseased in year t will produce proportionally s less than healthy vines—thus revenue from healthy vines is multiplied by

$$(1-a\sum_{n=0}^{5}(1-b_n)d_{t-n-1}-sd_t).$$

The lifespan of the vineyard is 25 years, based on University of California Cooperative Extension (UCCE) Cost and Return studies (UCCE 2000-2011).

The age-specific yield from vines of age n years as a proportion of yield from mature vines, b_n, which was calculated from the age-specific yield table given in the UCCE Cost and Return study for Cabernet Sauvignon in Sonoma County (UCCE 2010), is given by Equation 2:

$$b_n=\begin{cases}0.0 \text{ if } n\le 2\\ 0.3 \text{ if } n=3\\ 0.7 \text{ if } n=4\\ 1.0 \text{ if } n\ge 5\end{cases} \qquad \text{(Eq. 2)}$$

The disease incidence in year t, d_t, is given in Equation 3:

$$d_t=d_{t-1}(1-a+g+d_0a)+e, \qquad \text{(Eq. 3)}$$

and is a function of:

d_{t-1}, the disease incidence in the previous year;
a, the proportion of diseased vines that are rogued and replaced each year;
g, the rate of disease spread within the block;
d_0, the rate of disease in new vines that have not been screened for GLRaV-3; and
e, the disease entering from neighboring blocks.

We assumed a maximum for d_t of 75% after consultation with University of California, Davis plant pathologists, who suggested that over long periods of time, infection tends to plateau (Kari Arnold, Farm Advisor and past Dept. of Plant Pathology graduate student researcher, and Neil McRoberts, Associate Professor of Plant Pathology, personal communication, 2018). Note that the maximum of 75% is not what one would expect to find in a randomly selected vineyard, but rather the upper limit that would be reached over a long period of time if leafroll were allowed to spread through the vineyard unchecked. Because of the recursive structure of the disease incidence, given in Equation 2, incidence in any year is influenced by the incidence in newly purchased (unscreened) vines, d_0. Hence, incidence in any year in the life of the vineyard, m, can be defined as a function of d_0:

$$d_m=d_0(1-a+g+d_0a)^m+em \qquad \text{(Eq. 3′)}$$

Net income per representative hectare was calculated using parameters derived from a range of sources. Table 1 provides information on yield, area planted, and price. Table 2 presents other baseline parameter values and their sources. In 2010, growers in the North Coast region received an average ~\$2782/t_m crushed grapes (CDFA 2011b). Average yield was 7.40 t_m/ha, so the average revenue was ~\$20,581/ha (CDFA/NASS 2011a, 2011b). Planting density was 3266 vines/ha, a simple average of planting densities in Napa and Sonoma counties given in the UCCE Cost and Return studies (UCCE 2000-2011). The replacement cost for diseased vines that are rogued and replaced was also calculated from the UCCE Cost and Return studies. The vine replacement cost was \$14.45/vine, which included labor, the vine itself, fertilizer, and other inputs. A range of values for the amount of GLRaV-3 entering from neighboring properties was used, with a linear increase of 1.5% of vines/ha/yr as the baseline.

Conversations with several nursery managers indicated that unscreened vine stock was most often propagated when growers provided cuttings of a "special" clone or heritage selection from field vineyards to nurseries as a custom order. We assumed the fields from which the selections were taken had a baseline GLRaV-3 incidence of 30%, according to discussion with the scientists who conducted the virus testing. However, since symptoms are often visually recognized, and growers are unlikely to furnish nurseries with stock that is

Table 2 North Coast region parameter values.

Variable	Symbol	Value	Source
Price (\$/t_m)	P	2782	CDFA/NASS[a] 2011b
Yield (t_m/ha)	Y	7.40	CDFA/NASS 2011a and 2011b
Diseased vines replanted (%/yr)	a	90	Assumption
Yield reduction for diseased vines (%)	s	35	Based on range of values from Komar et al. 2010, Moutinho-Pereira et al. 2012, and Walter and Legin 1986.
Planting density (vines/ha)	v	3267	UCCE[b] cost studies
Replacement vine cost (\$/vine)	r	14.45	UCCE cost studies
Additional cost for GLRaV-3-screened vines (\$/vine)	c	0.048	Foundation Plant Services (see fpms.ucdavis.edu/WebSitePDFs/Forms/UserFeeDiagram.pdf)
Cost to monitor for leafroll symptoms (\$/ha)	m	20	Grower interviews
Disease spread rate (% of last year's disease incidence)	g	10	Almeida et al. 2013
Disease incidence in nonscreened vines (%)	d_0	10	Assumption; sensitivity analysis conducted
Disease entering from other blocks (%/yr)	e	1.5	Assumption; sensitivity analysis conducted
Real discount rate (%/yr)	n/a	3	Assumption

[a]CDFA/NASS: California Department of Food and Agriculture/National Agricultural Statistics Service.
[b]UCCE: University of California Cooperative Extension.

symptomatic, we assumed that the rate of GLRaV-3 in the unscreened stock is one-third that of the field (i.e., 10%) as a baseline, and conducted a sensitivity analysis for alternative GLRaV-3 incidence rates (5 and 30%) in the unscreened stock. Yield is reduced by 35% in any infected vine, a conservative estimate for yield loss in light of available studies (e.g., Walter and Legin 1986, Komar 2010, Moutinho-Pereira 2012).

Using the parameterization above, since we assumed 30% of vines in the field on average were infected with GLRaV-3 in this region, and those infected vines on average had a 35% lower yield, average yield/ha would have increased by 10.5% if all vines were free from GLRaV-3. Comparing the average revenue per hectare given average yields at the time of this study ($20,581/ha), with the revenue/ha if the block had no GLRaV-3 infection ($22,743/ha), the cost of the disease at the time of this study, not accounting for price effects, was $2162/ha, or 10.5% of $20,581. Scaling up over the 40,640 ha of bearing vines in that region, the cost of the disease for the North Coast at the time of this study was $88 million annually. This number included only the value of forgone yield in a given year, not additional costs of GLRaV-3 infection prevention such as spraying for mealybugs, or the cost of vine replacement.

Results and Discussion

Economic losses from GLRaV-3. The losses from GLRaV-3 in the North Coast region were estimated under various scenarios for using GLRaV-3-screened stock and replanting diseased vines (Table 3). These values were calculated using Equation 1, so they took into account the cost of vine replacement, years in which young vines were not yet bearing or not yet fully bearing, and additional costs for GLRaV-3-screened vines. Among the scenarios considered, losses were greatest when growers planted initially with unscreened vines and then did not replant; growers lost an average $2643/ha/yr in this scenario, with a net present value of $66,063 over the vineyard's 25-year lifetime (Table 3, row six). Losses were minimized when growers initially planted with GLRaV-3-screened vines and then rogued and replanted with GLRaV-3-screened vines (Table 3, row one). Under that scenario, GLRaV-3-induced losses were ~$1515/ha/yr, with a net present value of $37,875 over the 25-year lifespan of the vineyard. These minimized losses represent damages imposed by disease entering from neighboring blocks, illustrating the importance of the behavior of neighboring landowners, which is discussed in detail below.

Benefits from planting GLRaV-3-screened stock. The benefits to growers from using GLRaV-3-screened vines were estimated by comparing scenarios in which plantings and replantings were done with GLRaV-3-screened vines versus plantings and replantings with unscreened vines. Nurseries that use FPS materials (GLRaV-3-screened or not, but most of these are screened) must pay a surcharge of $0.008 to $0.048 per grapevine sold. Interestingly, in informal interviews, most nurseries reported charging the same price for virus-screened and unscreened vines. Since virus-screened vines are on average healthier, they are more productive, and nursery managers estimated that their savings from using virus-screened vines were worth more than the assessment, so they did not pass the fee on to growers. The benefit from the provision of GLRaV-3-free vines was computed as the difference in variable profit between (a) a hectare initially planted in GLRaV-3-screened vines and then rogued and replanted with screened vines, and (b) a hectare planted and replanted with vines that have not been screened for GLRaV-3. Alternatively, the benefit from the GLRaV-3-screened vines can be computed as the difference in losses between a hectare planted and replanted with GLRaV-3-screened vines and a hectare planted and replanted with unscreened vines (Table 3).

The benefits to growers from choosing GLRaV-3-screened vines over unscreened vines, both for initial planting and for replanting to replace diseased vines were calculated for a representative hectare and for the North Coast region as a whole (Table 4, row two). To illustrate, using the baseline of 10% GLRaV-3 incidence in unscreened vines (Table 4, row two), a representative hectare planted with GLRaV-3-screened vines, managed by roguing and replacing diseased vines with GLRaV-3-screened vines, was projected to earn an annual average variable profit of $11,683 (allowing for a charge of $0.048 for FPS-sourced vines). That same hectare, if planted and replanted with unscreened vines (and thus without the fee), had a projected annual average variable profit of $11,129/yr. Thus, the value of GLRaV-3-screened vines for that hectare was $554/yr, and it was cost-effective for growers to choose GLRaV-3-screened vines over unscreened. These measures of variable profit, $11,683 and $11,129, respectively, reflect only leafroll-related costs, because other variable costs were held constant in the comparison. Scaling up by the 40,640 ha in the region and

Table 3 North Coast losses from Grapevine Leafroll associated Virus-3 (GLRaV-3).

		Average annual discounted value over 25 years		Net present value over 25 years	
Plantings	Replantings	Per ha ($/ha/yr)	Entire region ($ in millions/yr)	Per ha ($/ha)	Entire region ($ in millions)
(1) GLRaV-3-screened	GLRaV-3-screened	1515	61.6	37,875	1539.2
(2) GLRaV-3-screened	Non-GLRaV-3-screened	1691	68.7	42,272	1717.9
(3) GLRaV-3-screened	No replanting	1880	76.5	46,988	1909.6
(4) Non-GLRaV-3-screened	GLRaV-3-screened	1839	74.7	45,981	1868.7
(5) Non-GLRaV-3-screened	Non-GLRaV-3-screened	2069	84.1	51,722	2102.0
(6) Non-GLRaV-3-screened	No replanting	2643	107.4	66,063	2684.8

assuming 100% adoption of GLRaV-3-screened vines, the total potential benefit from using GLRaV-3-screened vines was \$22.5 million/yr. This is much less than the estimate of \$88 million, which reflected the gain if the disease were entirely eliminated at no cost. Nevertheless, it represents 2.7% of the average annual North Coast region grape crush revenue of \$839.6 million over the five years in the period of 2007 to 2011.

The estimated value of the GLRaV-3 screening program varied depending on the counterfactual scenario and the baseline disease incidence in the field. If the disease incidence for unscreened vines was assumed to be 5% rather than 10% (Table 4, row one), the annual benefit/ha from using GLRaV-3-screened vines was projected to be \$253, and the regional value \$10.3 million, or ~1.2% of the regional revenue. If the incidence in unscreened vines was assumed to be as high as 30% (Table 4, row three)—the estimated in-field baseline incidence—then the average annual value/ha of the GLRaV-3 screening program was projected to be \$2365, with a regional value of \$96.1 million, or 11% of regional revenue.

The benefit of roguing and replanting diseased vines. Comparing the losses for a hectare planted with GLRaV-3-screened vines and rogued and replanted with GLRaV-3-screened vines (Table 3, row one) versus a hectare planted with GLRaV-3-screened vines but not replanted at all (Table 3, row three), the hectare that was rogued and replanted yielded an additional variable profit of \$365. If all growers followed the same strategy, instead of not roguing and replacing, the North Coast region would gain \$14.8 million/yr. If the vineyard was planted with unscreened vines and diseased vines were rogued and replanted with GLRaV-3-screened vines, the average annual benefit from roguing and replanting was \$803/ha, and the regional value was \$32.6 million (comparing rows four and six of Table 3). If a grower used unscreened vines for both initial planting and replanting, the average value of replanting was \$574 (comparing rows five and six of Table 3). The grower would be better off replanting with GLRaV-3-screened vines.

The benefits from the GLRaV-3 screening program also changed with the replanting scenario. Rows one and two of Table 5 show the benefits from planting with GLRaV-3-screened vines initially, when replanting either did not take place (row one) or was done with unscreened vines (row two). In all cases, there was a net benefit to initial planting with screened vines. The benefit from initial planting and then replanting with screened vines over both planting and replanting with unscreened vines was \$554/ha/yr, or \$22.5 million for the region annually (Table 5, row three). The greatest benefit from initial planting with GLRaV-3-screened vines was achieved when comparing the two scenarios in which the vines were not replanted: the benefit from initial planting with screened vines was \$763/ha. However, overall losses were minimized—and therefore, variable profit measures were maximized—when growers initially planted with screened vines and then rogued and replanted with screened vines (Table 3). Our estimates of a positive net benefit from roguing and replacing symptomatic vines over a range of scenarios are consistent with findings that the optimal leafroll management strategy in Napa and Sonoma counties, over a range of scenarios, was either roguing and replacement with vector control or replacing the entire vineyard (Ricketts et al. 2015).

Impact of control strategy used by neighbors. Because leafroll can spread between properties, actions by individual growers may have a significant impact on their neighbors, representing a positive or negative externality. Data on disease entry from other properties at a representative scale are lacking, and this aspect of the problem depends on many factors. To examine the potential effect of disease entry from surrounding properties, we assumed a baseline disease entrance of 1.5%/yr from neighboring properties after discussion with University of California, Davis plant pathologists (Kari Arnold, Farm Advisor and past Department of Plant Pathology graduate student researcher, and Neil McRoberts,

Table 4 Grower net benefits from planting and replanting with Grapevine Leafroll associated Virus-3 (GLRaV-3)-screened vines.

Disease incidence in non-GLRaV-3-screened vines (%)	Average discounted annual benefit			Net present value over 25 years		
	Per vine (\$/vine/yr)	Per ha (\$/ha/yr)	Entire region (\$ in millions/yr)	Per vine (\$/vine)	Per ha (\$/ha)	Entire region (\$ in millions)
(1) 5	0.08	253	10.3	1.94	6335	257.5
(2) 10	0.17	554	22.5	4.24	13,847	562.7
(3) 30	0.72	2365	96.1	18.10	59,129	2403.0

Table 5 Grower net benefits from planting Grapevine Leafroll associated Virus-3 (GLRaV-3)-screened vines.

	Average annual discounted benefit			Present value of net benefits over 25 years		
Planting strategy	Per vine (\$/vine/yr)	Per ha (\$/ha/yr)	Region (\$ in millions/yr)	Per vine (\$/vine)	Per ha (\$/ha)	Region (\$ in millions)
Without replanting	0.23	763	31.0	5.84	19,075	775.2
Replanting with non-GLRaV-3-screened vines	0.12	378	15.4	2.89	9450	384.0
Replanting with GLRaV-3-screened vines	0.17	554	22.5	4.24	13,847	562.7

Associate Professor of Plant Pathology, personal communication, 2018). A sensitivity analysis over alternative values for disease entrance is also presented. Because disease pressure coming from outside the grower's control is ongoing, eradication of GLRaV-3 is not possible in the baseline case and may not be possible at all (e.g., Atallah et al. 2015). Nevertheless, it is useful to examine the impact of the disease and vectors entering from outside to determine whether a cooperative control strategy, or even paying a neighbor to control the disease, could be economically beneficial.

The average annual cost/ha of disease entering the vineyard of a given grower (Grower A) from a neighboring property, owned by Grower B, was computed by comparing the variable profit/ha when no virus enters from the neighboring property with variable profit/ha when disease does enter (Table 6). At the baseline of disease coming from Grower B's property into Grower A's vineyard and infecting 1.5% of the vines/yr, the annual value of this spatial externality ranged from \$799 to \$1873/ha. The low end of this spectrum is the value/ha when Grower A planted with unscreened vines and did not replant. In this situation, Grower A already had relatively low variable profit because of the disease incidence in the original vines and subsequent spread, so the impact of the externality was relatively small. The greatest impact occurred when Grower A planted with GLRaV-3-screened vines, but did not replant. In this scenario, Grower B's property was the only source of the disease, but disease incidence increased over time since A did not rogue or replace vines.

The value of the externality when disease pressure entering from neighboring blocks is low (0.5%/yr) or high (3.0%/yr) is also presented (Table 6). The annual impact was least, at \$370/ha, when neighboring disease pressure was low and Grower A planted with unscreened vines and replanted with GLRaV-3-screened vines. At the opposite extreme, when neighboring disease pressure from Grower B was high and Grower A planted with either screened or unscreened vines, but replanted with unscreened vines, the value of the externality was \$3340/ha/yr—higher than if Grower A simply did not replant. The costs of monitoring, roguing, replacement, and the opportunity costs of newly replaced vines that are not yet bearing, were greater than the benefit from reducing disease introduction.

The regional benefits from planting GLRaV-3-screened vines. The analysis so far calculated the benefits/ha of vines under various assumptions about disease pressure and management strategy. To scale these vineyard-level measures up to the region as a whole required making assumptions about disease incidence and the adoption rate of the different strategies. The estimate of the difference in variable profit/ha between the current scenario and one in which unscreened vines are planted everywhere possible, can be interpreted as an estimate of the cost saving/ha between the current scenario and a hypothetical alternative scenario in which no GLRaV-3 screening exists. If this saving were applied to every hectare in the North Coast region, the resulting scaled-up measures could be interpreted as a measure of the "gross annual benefits" from GLRaV-3 screening. This measure corresponds to the economic surplus measure of the gross annual benefits from a technological change, in a supply and demand framework, drawing on more general approaches (Alston et al. 1998) as described specifically for this application in the Supplemental Data for this paper.

With that interpretation and some modest additional assumptions, it is possible to estimate the distribution of total benefits, as they are partitioned between winegrape producers and buyers. Specifically, the share of gross annual benefits going to consumers is approximately equal to $\varepsilon/(\varepsilon+\eta)$, where ε is the elasticity of supply (the percentage increase in quantity supplied in response to a 1% increase in price), η is the absolute value of the elasticity of demand (the percentage reduction in quantity demanded in response to a 1% increase in price), and the share going to producers is equal to $\eta/(\varepsilon+\eta)$.

The change in total economic surplus is heavily dependent on d_0, the disease incidence in newly purchased, unscreened vines. The best estimate for that value is 10%, as discussed above. However, if new vines have the same incidence as vines in the field, d_0 would be 30%. Sensitivity analysis using a lower value of 5% is also presented. Estimates for elasticities of supply and demand were previously published (Fuller and Alston 2012); the elasticity of demand for winegrapes was either -7 or -9.5, depending on the method of calculation; -7 was used here. The elasticities of supply of winegrapes were also reported as ranging from 0.1 (very short run) to 2.8 (long run; Alston et al. 2013); however, the more pertinent estimates are those corresponding to the greater values for the supply elasticity.

Benefits were estimated based on the ranges of elasticities (Table 7). All calculations assumed 100% adoption of the strategy defining the relevant scenario. The total estimated

Table 6 Annual discounted cost per hectare when Grapevine Leafroll associated Virus-3 (GLRaV-3) enters from neighboring property.

		Annual disease incidence from neighboring property		
Plantings	**Replantings**	**Low (0.5%) (\$/ha/yr)**	**Baseline (1.5%) (\$/ha/yr)**	**High (3.0%) (\$/ha/yr)**
GLRaV-3-screened	GLRaV-3-screened	498	1494	2988
GLRaV-3-screened	Non-GLRaV-3-screened	557	1671	3340
GLRaV-3-screened	No replanting	751	1873	2553
Non-GLRaV-3-screened	GLRaV-3-screened	498	1494	2988
Non-GLRaV-3-screened	Non-GLRaV-3-screened	557	1670	3340
Non-GLRaV-3-screened	No replanting	370	799	1135

Table 7 Annual discounted regional economic benefits from the Grapevine Leafroll associated Virus-3 (GLRaV-3) screening program.

	$ in millions/yr		
d_0 = 5%[a]			
Consumer surplus (ΔCS)	0.15	1.51	2.94
Producer surplus (ΔPS)	10.15	8.79	7.36
Total (ΔTS)	10.30	10.30	10.30
d_0 = 10%			
Consumer surplus (ΔCS)	0.32	3.29	6.43
Producer surplus (ΔPS)	22.19	19.22	16.08
Total (ΔTS)	22.51	22.51	22.51
d_0 = 30%			
Consumer surplus (ΔCS)	1.35	14.07	27.46
Producer surplus (ΔPS)	94.77	82.05	68.66
Total (ΔTS)	96.12	96.12	96.12

[a]d_0: Disease incidence in non-GLRaV-3-screened vines (%).

annual benefit from the program ranges from ~$10 million with 5% GLRaV-3 incidence in the newly purchased vines, to over $96 million if unscreened vines had 30% disease incidence. The elasticities of supply and demand for winegrapes play a role in determining the relative impact on producers of winegrapes and on those who purchase them. When supply is inelastic relative to demand, producers bear a greater share of total losses than when supply is more elastic relative to demand. Because of the perennial nature of the crop and the lag between planting decisions and harvest, supply is relatively inelastic and winegrape producers face greater losses than consumers. Demand is very elastic, even when using the more conservative published estimate (Fuller and Alston 2012).

At our best estimate of 10% GLRaV-3 incidence in unscreened vines (d_0 = 10%), the total benefit from the provision of clean vines to North Coast vineyards was $22.5 million/yr, or roughly 2.7% of the region's annual winegrape revenue. The vast majority of that benefit accrued to winegrape producers: the producer benefit was estimated at $16.1 (with ε = 2.8) to $22.2 million/yr (with ε = 0.1). The benefit to consumers, i.e., buyers of the winegrapes from the North Coast region, was estimated at $0.3 to $6.4 million/yr. For growers, the smallest expected net present value of the benefit from planting GLRaV-3-screened vines, over the 25-year expected life of the vine, was $2.89/vine (if growers initially planted with GLRaV-3-screened vines and then rogued and replanted with unscreened vines). With the maximum premium for GLRaV-3-screened vines of $0.048/vine, the benefit:cost ratio for growers was at least 60:1.

Conclusion

This work underscores the value of the GLRaV-3 screening program to winegrape growers in California's North Coast region. It highlights the economic impact of viruses—in particular, when spread between and within vineyards—on growers and winegrape growing regions. Even if growers pay a premium of $0.048/GLRaV-3-screened vine, they will reap a very large benefit—over 60 times the cost—from doing so at current costs.

The GLRaV-3 screening program enables growers to plant GLRaV-3-free material, from which the benefits are large relative to the costs. Our best estimates suggest that, for those who plant GLRaV-3-free material, the GLRaV-3 screening program yields a benefit of $0.17/vine, or $554/ha. With 100% adoption in the North Coast region, this translates to $22.5 million/yr, or roughly 2.7% of the winegrape revenue in the region. The FPS grapevine screening program averaged ~$2 million annually from 2007 to 2011 (Foundation Plant Services 2008-2012), so the benefit:cost ratio of that program for just one virus, GLRaV-3, in the North Coast region alone, is more than 10:1.

A number of caveats should be mentioned. First, these estimates include only the benefits to a single region, stemming from efforts to prevent the spread of a single disease. Total benefits would be much greater when other regions and viruses are also considered. However, appropriate data are not available to allow analysis of the benefits from screening for other viruses, nor of the benefits from GLRaV-3 screening accruing to other grapegrowing regions. Second, the model necessarily abstracts from some technical details about the spatial dynamics of the disease. Lacking appropriate information for California vineyards, we did not consider any duration of disease latency, nor did we explicitly model yield decline over time for diseased vines. While the economic impact of disease entering from a neighboring vineyard was part of the sensitivity analysis presented here, vine-to-vine spread was not explicitly modeled, nor were other spatial features that could lend more richness (and complexity) to the model. Expanding this model to include these vine-level details within the 1 ha representative unit of analysis, and to regions beyond California's North Coast, could help create a more comprehensive representation of the costs of GLRaV-3 and the benefits from virus screening. However, while a much more complex analysis along these lines might yield more nuanced estimates, it should not change the main results reported here, nor should it affect the findings concerning the total cost of the disease in the region, the benefits from screening for viruses, and the determinants of those benefits.

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