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The Benefits from Certified Virus-Free Nursery Stock: A Case Study of Grapevine Leafroll-3 in the North Coast Region of California

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ABSTRACT: Viruses and related pathogens have no cure and impose large costs on plant production. These diseases are typically spread through infected planting stock and plant propagation material. However, virus spread can be minimized if clean stock is used. We examine the costs and benefits of a virus testing and certification program for Grapevine Leafroll-3 in the North Coast region of California. We compare grower costs and benefits from using certified stock, and we extrapolate to the industry as a whole to estimate costs and benefits to consumers and producers of winegrapes, for the North Coast region. We find that the benefits from certification are large—in excess of $50 million per year for the region—and that they substantially outweigh the costs. We also find large potential benefits from roguing and replacing diseased vines rather than leaving them in the vineyard where they can spread disease. Additionally, we find large costs associated with disease entering from neighboring properties—nearly $300 per acre annually, using our baseline parameterization.

Key Words: Grapevine Leafroll Disease, perennial crop viruses, California wine and winegrapes

JEL Codes: Q12, Q13, Q16

1. Introduction

Viruses, viroids, virus-like agents and phytoplasmas comprise a class of plant pathogens for which no effective control is available to growers other than destruction of the plants themselves. Uncontrolled, these plant pathogens cause diseases of many crops that cost growers and consumers billions of dollars annually. In grapevines, the primary means of long-distance spread of these pathogens is the movement of infected planting stock and plant propagation material, and they can be controlled effectively if clean stock is made available to growers. Several grapevine clean plant centers have been established throughout the United States in an effort to provide virus-screened plants to nurseries and growers. These centers work in partnership with the United States Department of Agriculture (USDA) to provide a large inventory of plants, that are free from important viruses, to commercial nurseries that produce the planting stock for grape growers throughout the United States.

The costs of establishing and maintaining clean plant centers and producing disease-free grapevine stock have been documented, but comprehensive work has not yet been done to evaluate the benefits from those activities. We develop a framework for estimating the value of the benefits from the provision of virus-free plant materials at grapevine clean plant centers. We apply this framework in a case study of Grapevine Leafroll-3 (GLRaV-3), which is the dominant grapevine virus in California and worldwide (Tsai, et al., 2008), and which the American Vineyard Foundation (2012) has reported threatens the sustainability of the winegrape industry.

Several Grapevine Leafroll-associated viruses have been catalogued, of which Grapevine Leafroll-3 is only one. GLRaV-3 has a multitude of strains, some of which cause serious symptoms, while others do not cause symptoms at all. The virus expression varies across varietals as well. In most varietals, symptoms include the reddening of leaves, with their edges turning downward and rolling under, giving the disease its name. GLRaV-3 causes declines in production and fruit quality, in the form of decreased pigmentation, reduced sugar content, and delayed maturity. Yield reductions of 30% and more have been reported in studies of the effects of GLRaV-3 (Walter and Legin, 1986; Komar, et al., 2010; Moutinho-Pereira, et al., 2012). In some cases, the disease has also been linked to graft failure and young vine death (Golino, et al., 2002).

GLRaV-3 is vectored mainly by mealybugs, which are common in California vineyards (Golino, et al., 2002).[1] Grapevine Leafroll appears to be an increasing problem in California vineyards owing to increased mealybug populations, the presence of soft scale, the use of new rootstocks that are less tolerant of the pathogen, and new mutations in Leafroll strains (Carol, 2008). Control mechanisms for the disease are limited but include testing vineyard stock in the ground to learn of sources of inoculum, planting virus-free materials (both rootstock and scion), removal of diseased vines (sometimes an entire block), and spraying for mealybugs (Cooper, et al., 2012). However, studies have found pesticide and biocontrol mealybug treatments to be ineffective to date (Daane, et al., 2012).

In this paper, we calculate economic losses from GLRaV-3 in vineyards in Napa and Sonoma Counties in California, and the benefits from the use of virus-free materials to mitigate those losses. We develop a modeling framework in which we can allow for alternative scenarios for disease incidence, removal and replanting, spread of the disease within the vineyard, the effects of the disease on yield, crush prices of grapes, and several other pertinent characteristics. We estimate the change in economic welfare of producers and consumers resulting from the

[1] In California, the main vectoring mealybug species are (a) vine (*Plancoccus ficus*) (Tsai, et al., 2008) (b) obscure (*Pseudococcus viburni*), (c) longtailed (*Pseudococcus longispinus*), (d) citrus (*Planococcus citri*), and (e) grape (*Pseudococcus maritimus*) (Golino, et al., 2002).

presence of the disease, and from the availability of certified virus-free grapevines for the two counties. Our findings support and extend results from Atallah, et al. (2012), who found that removing diseased vines and replacing with certified virus-free stock is economically beneficial even though the costs of doing so are substantial (Atallah, et al., 2012b).

2. Previous Work

To the authors' knowledge, only one study of the economic impact of a virus protection program for plant materials has been conducted. Cembali, et al. (2003) examined the economic effects of National Research Support Program 5, a virus testing and clean plant provision facility located in Prosser, Washington. Using methods they attributed to Alston, et al. (1998), they calculated the benefits from avoiding yield losses and quality declines for apples, sweet cherries, and clingstone peaches, as a result of that center's program of testing and clean plant provision. Cembali, et al. (2003) estimated a total gross annual benefit of approximately $227 million, or 420 times the cost of the program. However, this article contains an error in its usage of the methodology presented by Alston, et al. (1998). The authors use a measure of the increase in yield associated with the program in place of what should be the corresponding equilibrium change in quantity produced and consumed, so the estimated effects of the program are inflated.[2]

While studies to date have not evaluated the benefits from certification or regulatory programs for Grapevine Leafroll, several studies have estimated the economic impact of the disease. Atallah, et al. (2012b) found that, if no control measures are implemented in a Cabernet

[2] Further questions can be raised about the use of a measure of change in yield as a measure of the horizontal shift in supply. The method we use avoids these problems because we estimate changes in variable costs directly. Their parameter λ is defined as the proportional change in equilibrium quantity, but is estimated as the proportional change in yield, which fails to account for adjustments made in response to the induced price changes.

Franc vineyard in the Finger Lakes region of New York, the cost of GLRa-V-3 ranges from (a) $25,407/ha with 30% yield loss and no quality penalty to (b) $41,000/ha with 50% yield loss and 10% quality penalty. They further found that initially planting certified virus-free stock rather than non-certified stock is financially rewarding over a 25-year horizon, even under the assumption that certified stock costs 25% more than non-certified stock. Among practices they evaluated, individually roguing vines was the most efficient and could reduce the losses to between $3,000 and $23,000 per hectare if the vineyard contained less than 25% Leafroll-infected vines, and replacing with certified virus-free stock would reduce losses further, down to approximately $1,800 per hectare (Atallah, et al., 2012a).

In a related article Atallah, et al. (2013) examined various control strategies using a plant-level spatial dynamic model of the disease. They found that roguing and replacing symptomatic vines and testing their four immediate neighbors was economically superior to all other strategies evaluated; compared with a no-control strategy it yielded benefits over 50 years having a net present value of $59,000 for a 5.2-acre vineyard. They found that incorporating the less-than-perfect detectability of diseased vines and allowing for the time lag before the vine becomes symptomatic added substantially to the measured disease costs over 25 years; a net present value of $25,000 versus $4,000 per hectare.

In an unpublished consulting report, Nimmo-Bell (2006) considered the economic impact of Grapevine Leafroll in a Sauvignon Blanc vineyard in Marlborough and a Merlot vineyard in Hawkes Bay, New Zealand, using a model calibrated with data collected from those vineyards over the years 1998–2005. They found a 6% gain in yields of infected vines versus clean vines in early years of infection, and a 47% loss in yield of infected vines versus clean vines in later years of infection. Data were not collected on the spread of the virus in the Marlborough vineyard, but the Hawkes Bay vineyard, which began with 1% of vines infected in 2000, was recorded as having 22% of vines infected in 2004. The authors found that a strategy of annual removal of infected vines was the most economic, while annual removal of infected vines along with their neighbors was second-best among those considered (Nimmo-Bell, 2006).

3. Program Costs in California

In California, the clean plant center responsible for testing, cleaning, and certification services of grapevines is Foundation Plant Services (FPS), at the University of California, Davis. FPS runs clean plant programs for numerous crops—grapes (raisin, table, and winegrapes), trees, roses, strawberry, pistachio, and sweet potato.

Income for FPS programs comes from a variety of sources: sales of plant materials to nurseries, a self-assessment on nurseries, and user fees of between $0.008 and $0.048 per plant sold, exchanged, or retained by nurseries that purchased the original vines from FPS; user fees are paid for both certified and non-certified materials.[3] The range is based on how the plant is sold: the minimum user fee of $0.008 is charged for grafted plants with only scion wood from FPS material; $0.048 is charged for the plants with both scion and rootstock from FPS material; $0.040 is charged for rootstock or own-rooted plants (Foundation Plant Services, 2011). Until recently, the fees were lower—half of what they are currently. However, in 2012, the nursery industry voted to increase the fees to earn more money for the FPS grape program, which had lost money several years in a row (Lamb, 2013). Public agencies such as the USDA's National

[3] The nursery self-assessment is managed by the California Department of Food and Agriculture (CDFA), and was voted into place by grapevine nurseries to support CDFA and FPS expenses associated with the grapevine and fruit tree certification programs.

Clean Plant Network (NCPN) and nonprofits, such as the American Vineyard Association, also contribute. Custom contracts and virus testing also bring in revenue.

Over the past five years, total annual income earned by the FPS from its grape program has averaged $1,781,483, while FPS expenses averaged $2,034,424 (with the main expenditures being staff salaries, benefits, contract labor, and operating expenses) such that, on net, the grape program has lost an average of $252,941 per year. In years when the grape program does not make money, programs for other crops may make up for the loss. The FPS earned an average annual net income of $106,062 over the past five years, but net income during those years has ranged a great deal—from a net gain of $128,537 in Fiscal Year 2010-11 to a net loss of $490,092 in the previous year. Over 20 years (Fiscal Year 1991-92 through Fiscal Year 2011-12) FPS earned an average net income of $49,604, and ranged from a net loss of $490,092 to a net gain of $588,584. In years when FPS income exceeds expenditures, funds are deposited into a reserve that can be utilized in years of loss (Lamb, 2013).

4. FPS Virus Testing and Cleaning, and the Path of Vines to the Vineyard

The path to certification is a long one; the timeline between submission of a rootstock or scion selection to FPS and availability of the selection can take as few as five years (the best-case scenario) or as many as nine years (if additional steps are necessary). In the best-case scenario, once selections arrive at FPS they are propagated to make more plants, and *field indexed*—grafted onto varieties that will stimulate disease symptoms for easy identification. In the second year, the field-indexed plants are screened for leaf and trunk symptoms of virus. For certain selections (for which an additional fee is paid), tissue culture begins in this year.[4] In year three, the test results are evaluated. If virus is evident, the plants are then put through tissue culture. If virus is not found, the selections are planted in the Foundation vineyard where they are subject to additional visual and lab testing in years four and five. In year five, certified, registered material is available to the grower or nursery who submitted it. Two years later, it is available to the general public for a fee.

However, if the plant must undergo tissue culture, the process from the initial culture to release is seven years instead of five years, as in the best-case scenario. After the initial culture, the plant is grown for two years before it is field indexed and lab tested. After that, the process is the same five-year process as for plants that are not found to have virus. The California Department of Food and Agriculture (CDFA) performs inspections at both FPS and at nurseries that sell FPS-sourced material, and provides a certification that the vines are virus-free.

5. Model

To estimate the value of losses incurred by winegrape growers as a result of grapevine diseases, and the benefit from using certified vines, we estimate differences in net revenue (or variable profit) from a representative acre of winegrapes between several scenarios. Specifically, for an "average" or "representative" strain of GLRaV-3, we compare scenarios for various aspects of disease pressure—initial disease incidence, disease spread, whether the vineyard was planted using certified vines, and whether the diseased vines are rogued and replaced. Leafroll

[4] Tissue culture is the cultivation of a very small number of cells from the tip of a plant shoot to produce another plant. Viruses typically do not reach this part of the plant, so cultivating the selection from these cells generally removes viruses from the selection. The remaining propagated plants are tested in the lab using a variety of methods in both the Spring and Fall.

characteristics vary greatly by region of California, as do winegrape yields, prices, and growing practices. We focus on a single region within California—Napa and Sonoma Counties (Table 1). This is the premier winegrape growing region in the United States, as well as the region with the most reported Leafroll.

[Table 1: *Winegrape Production in the Napa-Sonoma Region and California]*

5.1 Calculations of Losses from Disease

To estimate the costs of Leafroll and benefits from certification, we compute and compare "variable profit," defined for the purposes of this paper as gross revenue minus virus-related costs for a representative acre in Napa or Sonoma County. These costs include the labor and materials costs of roguing and replacement of diseased vines (including the price of the replacement vine itself), any price premium for certified vines, loss of production from reduced yield from diseased vines, and loss of production during the time when replaced vines are not yet bearing.[5]

In Equation (1), we provide an equation for variable profit, for a representative acre in this region, in the year *t* years after planting, where *t* ranges from 0 to 24.

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

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 per ton of winegrapes;

[5] Variable profit is defined as gross revenue per acre minus the costs of vine roguing and replacement for GLRaV-3, and charges for FPS-sourced vines. This "profit" has to cover overhead costs including capital recovery (depreciation), maintenance, and property taxes, as well as cultural costs not related to Leafroll, such as pruning, fertilizer application, and irrigation. These overhead costs are treated as fixed costs referring to factors that are held constant in the analysis, as we vary the treatment for GLRaV-3.

- *Y*, the yield, in tons per bearing acre, of mature vines without Leafroll;
- *a*, the proportion of diseased vines that are 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 acre;
- *s*, the proportion of yield lost from disease in diseased vines;
- *v*, the planting density, in vines per acre;
- *r*, the replacement cost per vine;
- *c*, the additional cost per vine for certified virus-free vines over non-certified vines (if vines are not certified, $c = 0$);
- δ_t, an indicator variable that is 1 if $t = 0$, and 0 otherwise—if growers initially plant their vineyard in certified vines, they pay the premium in $t = 0$; and
- *m*, the cost per acre to monitor for Leafroll symptoms (if no monitoring takes place, $m = 0$).

In year *t*, vines that were rogued and replaced in years *t* through t–2 will not produce, and vines that were rogued and replaced in years t–3 and t–4 will not bear at full capacity so they will bring in proportionally reduced revenue in the amount of $a\sum_{n=0}^{5}\left(1-b_n\right)d_{t-n}$. Vines that are diseased in year *t* will produce proportionally *s* less than healthy vines—thus revenue from healthy vines is multiplied by $\left(1-a\sum_{n=0}^{5}\left(1-b_n\right)d_{t-n}-sd_t\right)$. We assume the lifespan of the vineyard is 25 years, based on University of California Cooperative Extension (UCCE) Cost and Returns Studies (UCCE, 2000–2011).

The age-specific yield from vines of age *n* years as a proportion of yield from mature vines, b_n, is given by Equation (2):[6]

(2) $$b_n = \begin{cases} 0.0 \text{ if } n \leq 2 \\ 0.3 \text{ if } n = 3 \\ 0.7 \text{ if } n = 4 \\ 1.0 \text{ if } n \geq 5 \end{cases}$$

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

(3) $$d_t = d_{t-1}\left(1 - a + g + d_0 a\right) + e,$$

and is a function of:

- $d_{t\text{-}1}$, the disease incidence in the previous year;
- *a*, the proportion of diseased vines that were rogued and replaced;
- *g*, the rate of spread of the disease within the block;
- d_0, the rate of disease in new, non-certified replacement vines; and
- *e*, the disease entering from neighboring blocks.

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 (non-certified vines), d_0. Hence, incidence in any year in the life of the vineyard, *m*, can be defined as a function of d_0:

(3´) $$d_m = d_0\left(1 - a + g + d_0 a\right)^m + em$$

We calculate net income per representative acre using parameters derived from a range of sources. Table 2 presents baseline parameter values and their sources; see, also, Table 1. Growers in the Napa-Sonoma region received an average price of $2,524 per ton in 2010 (CDFA/National Agricultural Statistics Service (NASS), 2011b). However, the range of crush prices in this region is dramatic; in informal interviews, growers valued their grapes at between

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[6] The yield of vines of a given age relative to mature vines was calculated from the age-specific yield table given in the UCCE Cost and Return study for Cabernet Sauvignon in Sonoma County (2010).

$1,000 and $15,000 per ton. The average yield for that year was 3.30 tons per acre, so the average revenue is $8,329 per acre (CDFA/NASS, 2011b; CDFA/NASS 2011a). Planting density is 1,322 vines per acre.[7] The replacement cost for diseased vines that are rogued and replaced for that region is $14.45 per vine, which includes labor, the vine itself, fertilizer, and other inputs.[8] Based on unpublished data, we assume that GLRaV-3 enters from neighboring properties, linearly increasing the total population of infected vines per acre by 1.5% of all vines per acre per year. Many vineyard blocks in Napa and Sonoma counties are next to other vineyards, vineyard blocks, or other plants that harbor mealybugs and GLRaV-3 (Arnold, 2013).

[Table 2: *Napa-Sonoma Region Parameter Values*]

Conversations with several nursery managers indicated that non-certified vine stock is mostly provided by growers, from their vineyards, to nurseries to be propagated. We assume the fields from which the selections are taken have baseline GLRaV-3 incidence—30% based on expert opinion. However, since many disease symptoms are easily visually recognized and growers are unlikely to furnish nurseries with stock that is symptomatic, we assume that the rate of GLRaV-3 in the non-certified stock is one-third that of what is in the field (i.e., 10%) as a baseline, and conduct sensitivity analysis.

We assume, based on available studies, yield is reduced by 35% for vines that are infected in this region.[9] This is somewhat complicated by the fact that in this region yields are managed by hand-thinning, with a substantial proportion of grapes being dropped before they reach maturity. Consequently, if all diseased vines were replaced with clean vines, it is unlikely

[7] Planting density is calculated as a simple average over those two counties, using UCCE Cost and Return studies (UCCE, 2000–2011).

[8] Vine replacement cost is calculated from UCCE Cost and Return Studies (2000–11).

[9] Based on the studies we consulted—Komar (2010), Moutinho-Pereira (2012), and Walter (1986)—35% is a conservative estimate for yield loss.

that yield would increase by a full 35%. Therefore we conduct a sensitivity analysis that includes a range of values for this parameter.

To establish the current cost of the disease in the region, we compare the current variable profit with what it would be without GLRaV-3. Using the parameterization above, since 30% of vines in the field currently have Leafroll-3 in this region and those vines on average have a 35% lower yield than they otherwise would, average yield per acre would increase by 10.5% if all vines were GLRaV-3 free. Comparing the average revenue per acre given current yield ($8,329 per acre) with the revenue per acre if the block did not have any Leafroll-3 ($9,204 per acre), the current cost of the disease (not accounting for price effects), is $875 per acre (or 10.5% of $8,329). Scaling up over the 100,424 acres of bearing vines in that region, the current cost of the disease for Napa-Sonoma is $88 million annually. This number includes only the value of forgone yield in a given year so it excludes several elements of the costs of GLRaV-3. It does not include any of the costs of Leafroll prevention, such as spraying for mealybugs, and does not include costs of vine replacement.

[Table 3: *Napa-Sonoma Losses from Grapevine Leafroll 3*]

Table 3 contains estimates of the losses from Leafroll in Napa-Sonoma under various scenarios for using certified stock and replanting diseased vines. For all reported average annual values, we report the average of annual values discounted to the present, over a 25-year time-horizon, using a 3% discount rate. These values were calculated using Equation (1), so they take into account the costs of vine replacement, years in which young vines are not yet bearing, and additional costs for certified stock. Among the scenarios considered, losses are maximized when growers plant initially with non-certified stock and then do not replant diseased vines; growers lose an average of $1,095 per acre per year in this scenario, with a net present value of nearly

$30,000 over the vineyard's 25-year lifetime (row 6 of Table 3). Losses are minimized when growers initially plant with certified stock and then rogue and replant with certified stock (row 1 of Table 3). In that scenario, GLRaV-3-induced losses are approximately $600 per acre per year, with a net present value of $15,122 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 we discuss in detail in section 5.4.

5.2 Benefits from Planting Certified Stock

To estimate the benefits to growers from using certified stock, we can compare scenarios in which plantings and replantings are done with certified stock versus non-certified stock. Nurseries must pay a surcharge of between $0.008 and $0.048 per grapevine sold that uses FPS materials (certified or not, but most of these are certified). Interestingly, in informal interviews, most nurseries reported charging the same price for certified and non-certified vines. Since certified vines are virus-free, they are more productive and have fewer problems, and nursery managers estimated that their savings from using certified vines were worth more than the assessment, so they did not pass on the fee to growers. Additionally, nurseries interviewed stated that most non-certified vines are grower-furnished—generally specific selections from particular vineyards that were not publicly available and had not yet been put through the FPS screening process.

We compute the benefit from certification as the difference in variable profit from certified and non-certified vines as both initial plantings and replantings.[10] Table 4 presents benefits to growers for a representative acre, and for the Napa-Sonoma region as a whole, from choosing certified vines over non-certified vines both for initial planting and for replanting

[10] Alternatively, the benefit from certification can be computed as the difference in losses between an acre planted in certified and an acre planted in non-certified vines. Losses from Leafroll are given in Table 3.

diseased vines. To illustrate, using the baseline of 10% Leafroll incidence in non-certified vines (row 2), a representative acre planted with certified stock, managed by roguing and replacing diseased with certified vines, will earn annual average discounted variable profit of $4,736 (allowing for a charge of $0.048 for FPS-sourced vines). That same acre, if planted and replanted with non-certified vines (and thus without the fee), will have an average variable profit of $4,246 per year, so the value of certified stock for that acre is $533 per year, and it is cost-effective for growers to choose certified stock over non-certified.[11] Scaling up by the 100,424 acres in the region and assuming 100% adoption of certified stock, the total potential benefit from utilizing the certified stock is $53.5 million per year.[12] Over 25 years, the benefit from planting and replanting with certified stock is $10.08 per vine, $13,327 per acre, or $1.3 billion for the Napa-Sonoma region.

[Table 4: *Grower Net Benefits from Planting and Replanting with Certified Stock*]

The value of the certification program varies depending on the counterfactual scenario and the baseline disease incidence in the field. If the disease incidence for non-certified vines were 5% rather than 10% (see row 1 of Table 4), the annual benefit per acre from using certified stock would be $321, and the regional value would be $32.3 million—about 3.8% of the regional revenue. If the incidence in non-certified stock were as high as 30% (row 3 of Table 4)—the estimated in-field baseline incidence—then the average annual value per acre of certification is $3,284, with a regional value of $329.8 million, approximately 40% of regional revenue.

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[11] Recall, these measures of variable profit ($4,736 and $4,246, respectively) reflect only Leafroll-related costs because other variable costs are held constant for the purposes of our comparison.

[12] This is much less than the estimate of $88 million, which reflects the gain if the disease were entirely eliminated at no cost. Nevertheless, it represents roughly 7.3% of the average annual grape crush revenue in Napa-Sonoma of $839.6 million over the five years, 2007–2011.

5.3 The Benefit from Roguing and Replanting Diseased Vines

Notably, the choice to plant certified vines is less important than whether the vines are replanted regularly during the vineyard's lifetime. Comparing losses for an acre that is planted with certified stock and is rogued and replanted with certified stock (row 1 of Table 3), and an acre planted with certified stock but not replanted at all (row 3 of Table 3), the acre that is rogued and replanted gains additional variable profit of $185. If all growers followed the same strategy, compared with a strategy of not roguing and replacing, the Napa-Sonoma region would gain $18.6 million per year. If the vineyard is planted with non-certified stock, and diseased vines are rogued and replanted with certified vines, the average annual benefit from roguing and replanting is $181, and the regional value is $18.2 million (comparing rows 4 and 6 of Table 3). If a grower uses non-certified stock for both initial planting and replanting, the average value of replanting in this case is negative—the grower loses $43 per acre (comparing rows 5 and 6 of Table 3). In this case they are better off not replanting, or replanting with certified stock.

[Table 5: *Grower Net Benefits from Planting Certified Stock*]

The benefit from certification changes with replanting scenario as well. Rows 1 and 2 of Table 5 show the benefits from initially planting with certified stock when replanting either does not take place (row 1) or is done with non-certified stock (row 2). While the benefit is reduced in both of these scenarios compared to when vines are replanted with certified stock, using certified stock remains economically beneficial—the representative grower gains over $300 per acre per year, even when no replanting takes place. The greatest benefit from initially planting with certified stock is achieved when the vineyard is rogued and replanted with certified stock (row 3 of Table 5)—in this case, the benefit is $513 per acre.

If the disease incidence in the non-certified vines is high enough, however, replanting with non-certified vines becomes economically harmful; based on sensitivity analysis, if the disease incidence in the non-certified vines is 8% or greater using annual profits discounted to their present value, profits are higher if growers do not replant than if they replant with non-certified vines.

5.4 Impact of Neighboring Grower's Control Strategy

Because Leafroll can spread from one property to another, actions by individual growers may have a significant impact on their neighbors, a negative externality. We assume a baseline disease entrance of 1.5% per year coming from neighboring properties, which is the average from Arnold (2013), and was corroborated in discussions with growers and other academics. Because disease pressure coming from outside the grower's control is ongoing, eradication of Leafroll is not possible in the baseline case, and may not be possible at all (e.g. Atallah et al., 2013). 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, could be economically beneficial.

[Table 6: *Average Annual Value per Acre of Virus Entering from Neighboring Property*]

Table 6 shows the average annual value per acre of disease entering the vineyard of a given grower (Grower A) from a neighboring property, owned by Grower B. This value is computed by comparing the average annual variable profit per acre when no virus enters from neighboring property with variable profit when disease enters at varying rates. At the baseline of 1.5% disease coming from Grower B's property into Grower A's vineyard per year, the annual value of the spatial externality ranges from $286 up to $787 per acre. The low end of this spectrum is the value per acre when Grower A plants with non-certified stock and does not replant. In this situation, Grower A already has relatively low variable profit because of the disease incidence in the original stock and subsequent spread, so the impact of the externality is relatively small. The highest impact results when Grower A plants with certified stock, but does not replant. In this scenario, Grower B's property is the only source of the disease, but disease incidence increases over time since A does not rogue or replace vines,

We also examine the value of the externality when disease pressure entering from neighboring blocks is low (0.5% per year) or high (3.0% per year). The annual impact is minimized at $131 per acre when neighboring disease pressure is low and Grower A plants with non-certified stock and replants with certified stock. When neighboring disease pressure from Grower B is high and Grower A plants with certified stock and replants with non-certified stock, the value of the externality is $1,542 per acre per year—higher than if grower simply does not replant. The costs of monitoring, roguing, replacement and the opportunity costs of newly replaced vines that are not yet bearing, are greater than the benefit from reducing the disease spread.

5.5 The Regional Benefits from Virus-Free Certification

The analysis so far has referred to the benefits per acre of vines under various assumptions about disease pressure and management strategy. To scale these vineyard-level measures up to the region as a whole requires making assumptions about disease incidence and the rate of adoption of the different strategies. We use our estimate of the difference in variable profit per acre between the current scenario and one in which non-certified vines are planted everywhere possible, as an estimate of the cost saving per acre between the current scenario and one in which certification does not exist, and apply this saving to every acre in the Napa-Sonoma region. The resulting scaled-up measures can be interpreted as corresponding to a measure of "gross annual benefits" that correspond to economic surplus measures used to measure the benefits from technological change, in a supply and demand framework, as described by of Alston, et al. (1998) and as illustrated in the Appendix. Making that interpretation, with some modest additional assumptions we can further estimate the distribution of the benefits, including effects on growers, nurseries, and buyers of winegrapes. Specifically, the share of gross annual benefits going to consumers is approximately equal to $\varepsilon/(\varepsilon+\eta)$ where ε is the elasticity of supply and η is absolute value of the elasticity of demand, and the share going to producers is equal to $\eta/(\varepsilon+\eta)$, as described in the Appendix.

The change in total surplus is heavily dependent on d_0, the disease incidence in newly purchased, non-certified vines. Our best estimate for that value is 10%, as discussed earlier in the paper. However, if new vines were to have the same incidence as vines in the field, d_0 would be 30%. We also use a lower value of 5% in our sensitivity analysis. We use estimates for the elasticities of supply and demand from our other work; Fuller and Alston (2012) report the elasticity of demand for winegrapes as either −7 or −9.5, depending on the method of calculation, and we opted to use −7. Alston, et al. (2013) report elasticities of supply of winegrapes (ε) ranging from 0.1 (very short run) to 2.8 (long run), and we use that range, however the more pertinent estimates are those corresponding to the larger values for the supply elasticity.

[Table 7: *Regional Welfare Benefits from the Certification Program*]

We report a range of estimates for welfare change based on these ranges, presented in Table 7. All of these calculations assume 100 percent adoption of the strategy defining the relevant scenario. Total annual welfare gain from the program ranges from approximately $32.3 million with 5% GLRaV-3 incidence in the newly purchased vines, up to nearly $330 million if non-certified vines have 30% disease incidence. The elasticities of supply and demand for winegrapes play a role in the relative impact on producers of winegrapes and those who purchase them. When supply is inelastic compared to demand, producers bear a greater share of total losses than they do 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 using the more conservative estimate from Fuller and Alston (2012).

At our best estimate of 10% GLRaV-3 incidence in non-certified vines ($d_0 = 0.1$) the total benefit from the clean stock to North Coast vineyards is $53.5 million per year, or roughly 6.4% of the region's annual revenue. The vast majority of that is born by winegrape producers, but the change in producer surplus ranges from $38.2 (with $\varepsilon = 2.8$) up to $52.8 million per year (with $\varepsilon = 0.1$). The benefit to consumers—buyers of the winegrapes from the North Coast region—ranges from $0.75 to $15.3 million per year. For growers, the minimum expected net present value of the benefit from planting certified vines, over the 25-year expected life of the vine, is $5.78 per vine (if growers initially plant with certified stock and then do not rogue and replant diseased vines). With the maximum certification premium of $0.048 per vine, the benefit:cost ratio for growers is at least 120:1.

5. Conclusion

This work echoes similar studies conducted in New York State in that we find that the current costs of GLRaV-3 in California are substantial and that it is economically beneficial for vineyards to pursue a strategy of roguing and replanting vines with Leafroll symptoms, at least in cases where the initial incidence is not too high. Further, even if growers must pay a premium for certified virus-free vines, this work suggests that they will receive a very large benefit—over 100 times the cost—from doing so at current costs.

The model we have created could be used easily for other pests and diseases of grapes in California, such as the many other viruses that FPS tests for. It could be useful in assisting vineyard owners in choosing whether to combat Leafroll in their vineyards, and if so, what strategy they should utilize. On average, the most economically beneficial strategy is to plant initially with clean vines and to rogue and replace with clean vines.

The benefit from replanting vines rather than leaving them in the field to spread disease is dramatic. The average annual benefit from replanting is $0.14 per vine, or $185 per acre if certified materials are used to plant and replant. However, if the vineyard is initially planted with non-certified materials, growers will lose money from replanting if they are replanting with non-certified materials. If they replant with certified stock, they will benefit roughly the same amount as if they had initially planted with certified stock.

The certification program allows the planting of certified virus free material, from which the benefits are large relative to the costs. Our best estimates suggest that the certification program yields a benefit of $0.40 per vine, $533 per acre, and, assuming 100 percent adoption, $53.5 million per year in the North Coast, or roughly 6.4% of the winegrape revenue in the region, taking into account virus-free certification for only one particular virus, GLRaV-3. This work underscores the value of the certification program, the benefits from roguing and replacing diseased vines, and the economic impact that viruses, in particular intra- and inter-vineyard virus spread, can have on growers and winegrape growing regions.

Notably, this work includes only the benefits to a single region, from efforts to prevent the spread of a single disease. Total benefits are in fact much higher. Our analysis could be extended over the entire state and for the many viruses that FPS tests for. Much more complex analysis is also possible. Lacking appropriate information for California vineyards, we do not take into account any duration of disease latency, nor do we explicitly model yield decline over time for diseased vines. Much is also unknown about the spatial spread of the disease. While we model the economic impact of disease entering from a neighboring vineyard as part of our sensitivity analysis, we do not explicitly model vine-to-vine spread or other spatial features that could lend more richness (and complexity) to our model. Expanding our model to include these vine-level details within our one-acre representative region of analysis, as well as larger-scale issues such as regions beyond Napa-Sonoma, could be useful in creating a more comprehensive representation of the costs of Leafroll and the benefits from certification.

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References

Alston, J. M., K. B. Fuller, J. D. Kaplan, and K. P. Tumber. "The Economic Consequences of Pierce's Disease and Related Policy in the California Winegrape Industry." *Journal of Agricultural and Resource Economics* 38, no. 2. 2013: 269–97.

Alston, J. M., G. W. Norton, and P. G. Pardey. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Wallingford, United Kingdom: CAB International. 1998.

American Vineyard Foundation. *2012 Research Priority Survey Results* [Online]. 2012. Available: http://www.avf.org/results.html [Accessed 15 August 2013].

Arnold, K. Personal Communication. 28 May 2013.

Atallah, S. S., M. I. Gomez, and J. M. Conrad. "An Agent-Based Model of Plant Disease Diffusion and Control: Grapevine Leafroll Disease." Paper presented at the 2012 Annual Meeting, August 12–14, 2012, Seattle, Washington. 2012a.

Atallah, S. S., M. I. Gómez, and J. M. Conrad. "A Plant-Level, Spatial, Bioeconomic Model of Plant Disease Diffusion and Control: Grapevine Leafroll Disease." Draft Working Paper, Cornell University, Charles H. Dyson School of Applied Economics and Management. no. 2013-13. 2013.

Atallah, S. S., M. I. Gómez, M. F. Fuchs, and T. E. Martinson. "Economic Impact of Grapevine Leafroll Disease on Vitis Vinifera Cv. Cabernet Franc in Finger Lakes Vineyards of New York." *American Journal of Enology and Viticulture* 63, no. 1. 2012b.

California Department of Food and Agriculture/National Agricultural Statistics Service. *Annual Acreage Report* [Online]. Sacramento, CA: National Agricultural Statistics California Field Office. 2011a. Available: http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Acreage [Accessed 3 August 2012].

———. *Annual Crush Report* [Online]. Sacramento, CA: National Agricultural Statistics California Field Office. 2011b. Available: http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Crush [Accessed 3 August 2012].

Carol, B. Grapevine Leafroll Virus Increasingly a Problem in California Vineyards [Online]. Western Farm Press. 2008. Available: http://westernfarmpress.com/grape-leafroll-virus-increasingly-problem-california-vineyards-0 [Accessed16 September, 2013].

Cembali, T., R. J. Folwell, P. Wandschneider, K. C. Eastwell, and W. E. Howell. "Economic Implications of a Virus Prevention Program in Deciduous Tree Fruits in the US." *Crop Protection* 22, no. 10. 2003: 1149–56.

Cooper, M. L., R. P. P. Almeida, and K. M. Daane. *Grapevine Leafroll Disease: Management Strategies* [Online]. 2012. Available: http://www.vineyardteam.org/files/resources/Cooper,Monica.pdf [Accessed 14 February 2013].

Daane, K. M., R. P. Almeida, V. A. Bell, J. T. Walker, M. Botton, M. Fallahzadeh, M. Mani, J. L. Miano, R. Sforza, and V. M. Walton. "Biology and Management of Mealybugs in Vineyards." In *Arthropod Management in Vineyards*, 271-307: Springer. 2012.

Foundation Plant Services. *Annual Report 2012* University of California, Davis 2012.

———. *FPS User Fees--Propagative Units* [Online]. 2011. Available: http://fpms.ucdavis.edu/WebSitePDFs/Forms/UserFeeDiagram.pdf [Accessed 24 May 2013].

Fuller, K. B., and J. M. Alston. "The Demand for Winegrapes in California." *Journal of Wine Economics* 7, no. 2. 2012: 192–212.

Golino, D. A., S. T. Sim, R. Gill, and A. Rowhani. "California Mealybugs Can Spread Grapevine Leafroll Disease." *California Agriculture* 56, no. 6. 2002: 196–201.

Gómez, M., S. Atallah, M. Fuchs, T. Martinson, and G. White. "Economic Impact of the Grape Leafroll Virus (GLRV) in the Finger Lakes Region of New York." *Extension Bulletin* No. EB-2010-15, 2010.

Just, R. E., D. L. Hueth, and A. Schmitz. *Applied Welfare Economics*. Edward Elgar. 2008.

Komar, V., E. Vigne, G. Demangeat, O. Lemaire, and M. Fuchs. "Comparative Performance of Virus-Infected Vitis Vinifera Cv. Savagnin Rose Grafted onto Three Rootstocks." *American Journal of Enology and Viticulture* 61, no. 1. 2010: 68–73.

Lamb, C. Personal Communication. 13 June 2013.

Moutinho-Pereira, J., C. Correia, B. Gonçalves, E. Bacelar, J. Coutinho, H. Ferreira, J. Lousada, and M. Cortez. "Impacts of Leafroll-Associated Viruses (GLRaV-1 and -3) on the Physiology of the Portuguese Grapevine Cultivar 'Touriga Nacional' Growing under Field Conditions." *Annals of Applied Biology* 160, no. 3. 2012: 237–49.

Nimmo-Bell. *Report for New Zealand Winegrowers: The Economic Effects and Financial Impact of GLRaV3* A Nimmo-Bell Publication 2006.

Tsai, C. W., J. Chau, L. Fernandez, D. Bosco, K. M. Daane, and R. P. P. Almeida. "Transmission of Grapevine Leafroll-Associated Virus 3 by the Vine Mealybug (Planococcus ficus)." *Phytopathology* 98, 2008: 1093–98.

University of California Cooperative Extension. *Cost and Return Studies* [Online]. Davis, CA: UC Davis Agriculture and Resource Economics. 2000–2011. Available: http://coststudies.ucdavis.edu/ [Accessed 27 August 2013].

———. *Sample Costs Fo Establish a Vineyard and Produce Winegrapes: Cabernet Sauvignon, Sonoma County* [Online]. 2010. Available: http://coststudies.ucdavis.edu/files/grapewinesonoma2010.pdf [Accessed 4 December 2013].

Walter, B., and R. Legin. "Connaissances Actuelles Sur Les Viroses De L'enroulement De La Vigne." *Le Vigneron Champenois* 9, 1986: 433–46.

Table 1: Winegrape Production in the Napa-Sonoma Region and California

(1) Production Region and Associated Districts	(2) Bearing Acreage, 2010	(3) Tons Crushed, 2010	(4) Yield per Acre, 2010	(5) Average Price, 2010
	Acres	*Thousands of Tons*	*Tons per Acre*	*2010$/ton*
Napa-Sonoma Region	**100,424**	**331**	**3.30**	**2,524**
Napa (District 3)	55,647	192	3.45	2,010
Sonoma and Marin (District 4)	44,777	139	3.10	3,236
State Total	**456,918**	**3,589**	**7.85**	**673**

Source: Column (2): CDFA/NASS (2011a); Columns (3)-(5): CDFA/NASS (2011b).

Table 2: Napa-Sonoma Region Parameter Values

	Symbol	Value	Source
Price ($/ton)	p	2,524	CDFA/NASS (2011)
Yield (tons/acre)	Y	3.30	CDFA/NASS (2011 and 2011a)
Diseased vines replanted (%/year)	a	90	Assumption
Yield reduction from disease (%)	s	35	Assumption
Planting density (vines/acre)	v	1,322	UCCE Cost Studies
Replacement vine cost ($/vine)	r	14.45	UCCE Cost Studies
Additional cost for certified virus-free vines ($/vine)	c	0.048	Foundation Plant Services (2011)
Cost to monitor for Leafroll symptoms ($/acre)	m	8	Grower interviews
Disease spread rate (% of last year's disease incidence)	g	11	Arnold (2013)
Disease incidence in non-certified vines (%)	d_0	10	Assumption
Disease entering from other blocks (%/year)	n	1.5	Arnold (2013); Gómez, et al. (2010)
Real discount rate (%/year)	n/a	3%	Assumption

Notes: SJV stands for San Joaquin Valley. CDFA/NASS is California Department of Food and Agriculture/National Agricultural Statistics Service. UCCE is University of California Cooperative Extension. Assumption in the Yield Reduction from Disease row is derived from Komar, et al. (2010), Moutinho-Pereira, et al. (2012), Walter and Legin (1986).

Table 3: Napa-Sonoma Losses from Grapevine Leafroll 3

	Plantings	Replantings	Average Annual Discounted Value over 25 Years		Net Present Value over 25 Years	
			Acre	Region	Acre	Region
			$/Acre/Year	*$ Millions/Year*	*$/Acre*	*$ Millions*
(1)	Certified	Certified	605	60.7	15,122	1,518.6
(2)	Certified	Non-certified	779	78.3	19,483	1,956.5
(3)	Certified	No Replanting	790	79.3	19,745	1,982.8
(4)	Non-certified	Certified	914	91.8	22,847	2,294.4
(5)	Non-certified	Non-certified	1,138	114.3	28,449	2,857.0
(6)	Non-certified	No Replanting	1,095	110.0	27,382	2,749.8

Table 4: Grower Net Benefits from Planting and Replanting with Certified Stock

	Disease Incidence in Non-Certified Stock	Average Discounted Annual Benefit			Net Present Value over 25 years		
		Per vine	Per acre	Region	Per vine	Per acre	Region
	%	*$/Year*	*$/Year*	*$ Millions/Year*	*$*	*$*	*$ Millions*
(1)	5	0.24	321	32.3	6.08	8,036	807.0
(2)	10	0.40	533	53.5	10.08	13,327	1,338.3
(3)	30	2.48	3,284	329.8	62.11	82,103	8,245.1

Table 5: Grower Net Benefits from Planting Certified Stock

	Average Annual Discounted Benefit			Present Value of Net Benefits over 50 years		
	Per vine	Per acre	Region	Per vine	Per acre	Region
	$/Vine/Yr	*$/Acre/Yr*	*$Mill./Yr*	*$/Vine*	*$/Vine*	*$ Millions*
Without Replanting	0.23	305	30.7	5.78	7,637	767.0
Replanting with Non-Certified Stock	0.27	359	36.0	6.78	8,966	900.4
Replanting with Certified Stock	0.40	533	53.5	10.08	13,327	1,338.3

Table 6: Average Annual Discounted Cost per Acre of Virus Entering from Neighboring Property

Plantings	Replantings	Annual Disease Incidence from Neighboring Property		
		Low (0.5%)	Baseline (1.5%)	High (3.0%)
			$/Acre/Year	
Certified	Certified	199	596	1,193
Certified	Non-certified	257	771	1,542
Certified	No Replanting	337	787	1,048
Non-certified	Certified	197	590	1,180
Non-certified	Non-certified	254	762	1,525
Non-certified	No Replanting	131	286	410

Table 7: Average Annual Discounted Regional Economic Benefits from the Certification Program

	ε=0.1	ε=1.2	ε=2.8
	$ Million per Year		
d_0=5			
Consumer Surplus (ΔCS)	0.45	4.72	9.22
Producer Surplus (ΔPS)	31.82	27.55	23.06
Total (ΔTS)	32.28	32.28	32.28
d_0=10			
Consumer Surplus (ΔCS)	0.75	7.83	15.30
Producer Surplus (ΔPS)	52.78	45.70	38.24
Total (ΔTS)	53.53	53.53	53.53
d_0=30			
Consumer Surplus (ΔCS)	4.65	48.26	94.23
Producer Surplus (ΔPS)	325.16	281.54	235.57
Total (ΔTS)	329.80	329.80	329.80

Notes: d_0 is the disease incidence in non-certified vines (%).

Appendix: Economic Surplus Calculations

We apply a version of the framework of Alston, et al. (1998) to illustrate changes in economic welfare for grapevine nurseries, consumers, and producers, assuming approximately linear supply and demand curves and a vertically parallel supply shift induced by the policy. The base case is the current one for which we have data, with the certification program in place, and the counterfactual alternative case is one without the program. Figure A-1 shows the shift in supply as well as areas representing the corresponding changes in consumer surplus (ΔCS) and producer surplus (ΔPS).

We begin with the equation for quantity supplied, where *P* is the crush price of grapes per ton and *k* is the vertical shift down in supply ($/ton) resulting from the availability of certified stock:

(A-1) $Q_S = \alpha + \beta(P + k)$

If k =0, the elasticity of supply, ε, is $\varepsilon = (\partial Q_S / \partial P)(P/Q_S)$, and also by definition, $\beta = \partial Q_S / \partial P$, then $\beta = \varepsilon Q_S / P$.

Quantity demanded is

(A-2) $Q_D = \gamma - \delta P$

We let η be the absolute value of the price elasticity of demand, $\eta = \left|(\partial Q_D / \partial P)(P/Q_D)\right|$. Then since $\delta = \partial Q_D / \partial P$, $\delta = \eta Q_D / P$. Setting supply equal to demand and solving for the equilibrium price, *P**, we obtain

(A-3) $P^* = \dfrac{-(\alpha + \beta k - \gamma)}{\delta + \beta}$.

The change in the equilibrium price implied by removal of the program is given as

(A-4) $\Delta P^* = P_1^* - P_0^* = -\frac{\beta k}{\delta + \beta}$,

and, expressing this change as a proportion of the initial price,

(A-4´) $Z = \frac{P_1^* - P_0^*}{P_0^*} = \frac{k}{P_0}\left(\frac{\beta}{\delta + \beta}\right) = -K\left(\frac{\varepsilon}{\eta + \varepsilon}\right)$,

where $K=k/P_0$. In our analysis, withdrawing the program, $K<0$ implies $Z>0$. The change in total surplus can be written

(A-5) $\Delta TS = P_0 Q_0 K\left(1 + 0.5Z\eta\right)$.

We can approximate the total surplus change by estimating the change in regional profits from the loss of the certification program:

(A-5') $\Delta TS \approx \pi_{NC} - \pi_C = P_0 Q_0 K$.

This estimate of the change in total surplus does not take into account the shaded triangle to the right of Q_1 in Figure A-1, but can be used as an approximation with relatively small supply shifts such as these.

The change in consumer surplus, ΔCS (area a + b + c) is:[13]

(A-6) $\Delta CS = -P_0 Q_0 Z\left(1 - 0.5Z\eta\right)$,

which can be approximated using a measure of the change in total surplus and the elasticities of supply and demand:

---

[13] Because we are modeling the derived demand for winegrapes at the farm level as an input into the production of wine, "consumer" surplus in the present context represents benefits accruing to the buyers of winegrapes and other intermediaries including final consumers of the wine those winegrapes are used to produce. Producer surplus includes the quasi-rents accruing to inputs used in farming and in nurseries; consumer surplus includes the quasi-rents accruing to off-farm processing, and marketing inputs as well as final consumer surplus. Economic rents typically refer to the difference between the costs of supplying a good and its market price. If some factors of production are fixed only in the short or intermediate term, the rents that accrue to them are called *quasi-rents.* See Just et al. (2008).

(A-7´) $\Delta CS \approx -P_0 Q_0 Z = \Delta TS \frac{Z}{K} = \Delta TS \frac{\varepsilon}{\varepsilon + n}$.

The change in producer surplus, ΔPS (area d + e + f) is

(A-8) $\Delta PS = -P_0 Q_0 \left(K - Z\right)\left(1 - 0.5Z\eta\right)$,

which can be approximated similarly using:

(A-8´) $\Delta PS \approx \Delta TS \frac{\left(K - Z\right)}{K} = \Delta TS \frac{\eta}{\varepsilon + \eta}$.

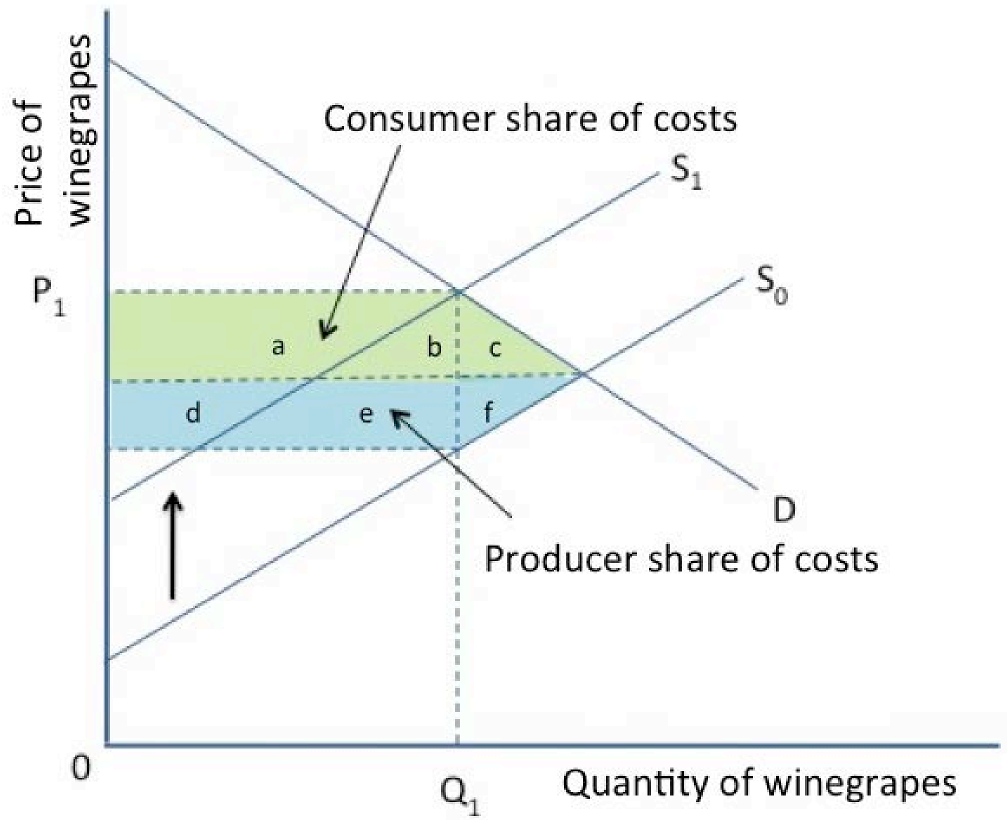

Figure A-1: Economic Welfare Change from Loss of Certification Program