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Economic Consequences of Pierce's Disease and Related Policy in the California Winegrape Industry

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Since 2000, approximately $50 million per year has been spent to control infestations of the Glassy-Winged Sharpshooter (GWSS), an insect that spreads Pierce's Disease (PD). This amount includes the costs of state and federal efforts to monitor and control the GWSS, research on PD/GWSS, and compliance with the PD Control Program. Using a simulation model of the market for California wine grapes, we estimate that under the current program, PD costs winegrape growers and consumers $92 million annually. If the program ended and the GWSS became widespread throughout California, the annual cost borne by growers and consumers would increase by an estimated $185 million.

Key words: California, invasive species, perennial crop model, Pierce's Disease Control Program, simulation model, wine grapes

Introduction

Pierce's Disease (PD) is a disease of grape vines that is caused by a strain of the bacterium *Xylella fastidiosa*. PD, which is endemic to California, has many host plant species and is spread by several species of insects called sharpshooters. PD can kill grapevines quickly, and scientists have not yet developed an effective cure or preventive measure. PD represents a significant threat to an industry that contributed $3 billion to the value of California's farm production in 2010 (including $0.9 billion in table grapes and raisins and $2.1 billion in wine grapes), and much more in terms of total value (USDA National Agricultural Statistics Service, 2011).

The main native vector of the disease is the Blue-Green Sharpshooter (BGSS), which has imposed chronic but generally manageable losses in the high-value Napa Valley and North Coast areas for at least a century. Major concerns about PD grew after a devastating outbreak in the Temecula Valley (in Southern California) in the late 1990s, spread by the newly arrived, nonnative Glassy-Winged Sharpshooter (GWSS). Compared with BGSS and other native sharpshooters, the GWSS can fly farther and feed on a greater variety of plants and plant parts and consequently have a much greater capacity to spread PD.

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Spurred by concern over this new vector's ability to spread PD, the California Department of Food and Agriculture (CDFA) developed an extensive program (the Pierce's Disease Control Program, or PDCP), which includes funding for research, area-wide controls, and inspections and focuses on preventing the spread of GWSS from south to north, in particular to Napa Valley, where GWSSs are not yet established. The control program requires nurseries to treat at their own expense all plant stock shipped northward, including ornamental species for urban areas. It also provides for inspections of those shipments both at the source and (in some cases) at the final destination and for maintaining GWSS traps in wine-growing regions statewide (California Department of Food and Agriculture and USDA National Agricultural Statistics Service, 2010). Public funds allow insecticide treatments to be offered to citrus growers free of charge in order to prevent the spread of GWSSs from citrus orchards to nearby vineyards in the Temecula Valley.

Using cost-accounting procedures, Tumber, Alston, and Fuller (2013) estimated that PD has cost approximately $105 million per year in recent years. This annual total includes approximately $48 million spent on preventive measures (including $7 million incurred by the nursery industry in compliance costs), public expenditures of about $40 million under the PD/GWSS program, and $56 million in vines lost and income forgone by winegrape growers, even while GWSSs are being held in check by these programs.

Funding for the PD/GWSS program is currently threatened by competing demands for state and federal funds, but little is known about the economic implications of changing or ending the program. This paper estimates the potential economic consequences in the California winegrape industry if the PD Control Program were to end as well as the expected benefits from continuing the present program.

To estimate these economic consequences, we developed a simulation model of supply and demand for California wine grapes that accounts for several unusual features of this particular pest-management policy problem. First, PD is a vector-borne disease with regional differences in vectors as well as the extent of the problem and its management, requiring a regionally disaggregated treatment. Second, wine grapes are long-lived perennials. Since PD kills vines, destroying productive capital and thus affecting production over multiple years, the disease is unlike typical agricultural pests and diseases that can be modeled as reducing yield within a season.[1] Finally, the quality of wine grapes varies markedly among producing regions within California, further necessitating regionally disaggregated treatment. We evaluate the aggregate impact of the disease as well as the benefits from the current control programs versus a no-program alternative over a range of scenarios for pest and disease prevalence. Our simulation results using our most likely parameter values indicate that PD currently costs the California winegrape industry approximately $92 million per year and would cost an additional $185 million per year if the PD Control Program were to end.

Model Overview

In our simulation of supply and demand for California wine grapes, each of six regions produces one of three regionally defined quality classes of wine grapes ("high," "medium," or "low"). Supply shocks such as disease outbreaks or the introduction of better pesticides can affect either individual regions or the state as a whole, but the supply regions are otherwise unrelated. Regions are linked on the demand side either because they produce grapes of the same quality (perfect substitutes) or through cross-price elasticities of demand. The demand side of the model is parameterized based on econometric estimates developed by Fuller and Alston (2012) for this purpose. Our main focus is the supply side of the model, including the representation of responses to prices, the nature of pest and disease prevalence, and market closure conditions. Neither the supply nor demand side of the

[1] Brown, Lynch, and Zilberman (2002) present a model of Pierce's Disease in the Napa Valley, but grapevines are not specified as durable capital in that model.

model is explicitly linked to markets outside California.[2] Our analysis focuses on California and its winegrape industry because, although PD is endemic in many other U.S. states, it is not a problem in other states that produce substantial quantities of wine grapes.[3]

The perennial nature of grapevines suggests that a dynamic model is necessary to capture the essential character of supply response. After planting, grapevines take several years to mature and can then remain economically productive for decades (typically 20–25 years, but often longer); thus, decisions regarding their planting and care can have effects that linger long into the future. This longevity is particularly relevant when considering the impact of a disease that destroys productive capital by killing healthy, mature vines, requiring substantial time to replace lost vines and for production to recover—a multi-period effect. We do not explicitly model the spatial dynamics of sharpshooter populations, but we do model the dynamics of vineyard age structure and production responses to PD losses, prices, and management strategies.

The model equations are specified as linear forms and are parameterized using recent values for prices, quantities, and acreage, combined with informed assumptions about elasticities and underlying trends in demand and yield.[4] The model starting points for prices, quantities, and acreage are the average actual values calculated from NASS/CDFA Crush and Acreage Reports for the years 2008–2010 (California Department of Food and Agriculture/National Agricultural Statistics Service 2009–2011). Values for the other parameters defining the supply side of the model were developed based on detailed data on costs and production and other knowledge about the economics of California winegrape production, combined with expert opinion and assessments based on specific knowledge of the industry, and informed experimentation. Details on the process used to elicit information about likely values for parameters of the model are reported in Appendix A, and details on the particular values used are reported in Appendix B.

In defining these parameter values we had in mind that the model would be used to simulate future responses, over a comparatively long period of time, to policy changes that can be regarded as fully anticipated and permanent. In recognition of uncertainty about the future prevalence of PD, alternative region-specific PD-induced death rates are tried in order to examine the implications for findings, and we present sensitivity analysis and discuss the robustness of the results. The basic model parameters—initial values for prices and acreage as well as initial and future values for yield—are held constant as we compare multi-year simulations of winegrape production and consumption under alternative PD scenarios.

Supply and Demand for Wine Grapes in California

Regional Aggregation

Regional disaggregation is appropriate in view of the significant variation in production methods, PD incidence, and prices of grapes produced in different California regions. Disease vectors, effective disease incidence, and control measures all vary greatly across the state. In the Napa and Sonoma Valleys, the main vector (the BGSS) has a strong preference for lush, new growth; additionally, pesticides are of limited use for controlling BGSSs. In some cases, growers can revegetate riparian areas with plants that do not attract the insect; in other cases, where prevalence is high, land is

[2] In our model, the California winegrape industry is implicitly connected on the demand side to the global and interstate wine industries because the elasticities of demand for California wine grapes as estimated reflect the fact that California wine competes with wine from around the world in domestic and international markets. The supply of wine grapes in California is not connected economically to the supply of wine grapes in other places, except implicitly through winegrape prices.

[3] In 2010, California accounted for 92% of total U.S. winegrape production, followed by Washington State with 5%, Oregon with 1%, and New York State with 1% (USDA National Agricultural Statistics Service, 2011). The overwhelming presence of PD and GWSS may have prevented the establishment of wine production using *vinifera* varieties (rather than PD-resistant native grape varieties) on a greater scale in states such as Texas and Florida.

[4] Fuller and Alston (2012) provide econometric estimates and other information about demand elasticities, but comparably useful estimates are not available for the supply side.

Table 1. Quality Classes and Production Regions—Definitions and Basic Statistics

Quality Class	Region	Crush Districts	Bearing Acreage, 2010	Tons Crushed, 2010	Yield per Acre, 2010	Average Price, 2010
			Acres	*Thousands of Tons*	*Tons per Acre*	*2010$/ton*
High	Napa-Sonoma	3,4	100,424	331	3.30	2,526
Medium	Coastal	5–7	55,266	313	5.66	971
	Northern California	1, 2 9, 10	37,489	165	4.38	904
	Northern SJV	11, 17	84,530	705	8.34	477
	Southern California	8, 15, 16	46,994	244	5.20	1,075
Low	Southern SJV	12–14	132,215	1,831	13.85	289

Notes: "SJV" refers to the San Joaquin Valley.

abandoned (Fuller, Alston, and Sanchirico, 2011). In Southern California, the main vector (the GWSS) is a nonnative, long-distance flyer that can feed on many different parts of the grapevine as well as hundreds of other plant species and subspecies. In this region, systemic insecticides are very effective in keeping sharpshooter populations low, a result of different soil types, temperatures, and insect behavior. The PD Control Program operates primarily to contain and suppress GWSSs in Southern California. All other parts of California face much lower, if any, pressure from PD, although in some cases the current large-scale prevention measures may have helped to maintain sharpshooter populations at their current (very low) levels.

Grape crush prices and yields also vary significantly across California. In the Napa and Sonoma Valleys, vineyards typically produce very few tons per acre at relatively high unit cost. In the Central Valley, where production styles are very different, vineyards can produce ten times the quantity per acre as those in Napa, but prices and costs per ton are much lower (California Department of Food and Agriculture/National Agricultural Statistics Service, 1981–2011). The rest of the state produces a range of wine grapes that falls between these two extremes in terms of price and yield. Within each region, prices and yields also vary significantly among varieties of the same color as well as between red and white winegrape varieties. However, for the purposes of this analysis we aggregate all varieties within each of the six production regions, which are defined as aggregates of crush districts on the basis of the volume-weighted average price per ton of grapes produced as well as the incidence and epidemiology of PD. Table 1 presents regional summary statistics on yields, prices, and production; figure 1 shows the location of the different regions within California.

Modeling Approach

Gray et al. (2005) reviewed models of supply response for perennial crops and found that the theoretically more defensible models partitioned the supply response into separate equations representing elements of yield per bearing acre and the number of bearing acres (or other measures of the stock of bearing vines), where adjustments to bearing acreage reflect planting and removal of vines, with a lag to reflect the time it takes for vines to come into production. In keeping with the vast majority of previous work on perennial crop supply response, we assume that the only supply response to price changes is through plantings (i.e., with no yield response to price and with removals based simply on the age of vines and random vine death) (Gray et al., 2005).

Our model includes an assumption that all vines are removed after twenty-five years, either for replacement with a new vineyard or for replacement with some other crop. The equations for the evolving age structure of planted acreage in the model explicitly reflect these removals. Vines in this model do not bear grapes until they are three years old, do not bear at their maximum yield until they are either five or six years old, and are assumed to bear at their maximum until they are removed after the harvest in their twenty-fifth year, consistent with typical California winegrape production

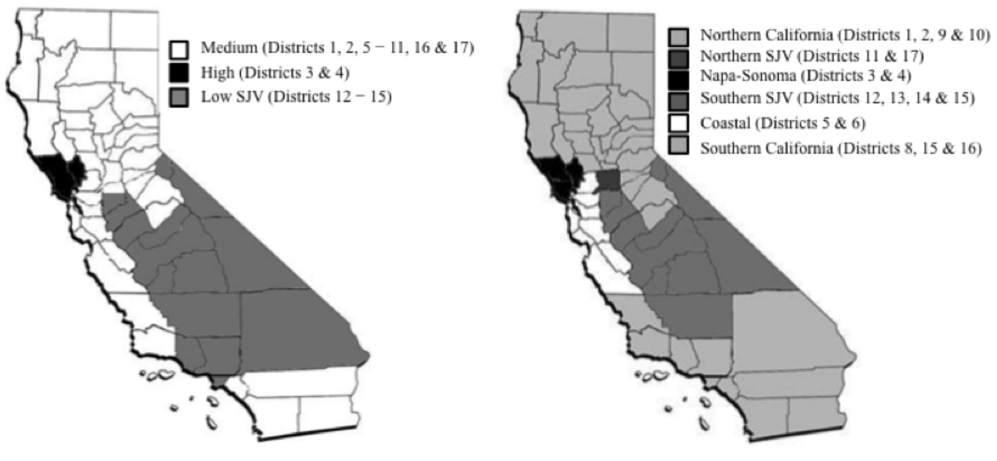

Figure 1. Quality Class (Left) and Production Regions (Right)

practices (University of California Cooperative Extension, 2000–2011).[5] Consequently, planting decisions today have implications for production and prices over at least the next twenty-five years. These decisions will therefore depend on expectations about prices, yields, and PD-induced losses over the life of the investment. We solve the model over two vineyard lifespans (fifty years).

Much of the published work on perennial crop supply response has used ad hoc models, without any formal connection to economic optimization, but some studies have argued for a modeling approach based on neoclassical investment theory.[6] We have adopted an approach based on that argument to model investments in new plantings over fifty years. The supply side of the model assumes competitive price-taking behavior by producers who maximize the present value of profits from investment in new plantings, taking account of the effects of region-wide planting decisions on both the cost of new plantings and on future output, prices, and variable costs. The model is applied separately in each of six distinct winegrape producing regions, which are treated as independent on the supply side but related through competition on the demand side of the market. The market equilibrium reflects the joint interaction of the supplies from the six regions with demand to determine the prices for the three different qualities of wine grapes. The development that follows next refers to a single region.

Investment in New Plantings

An investment in an acre of new plantings in year t will generate variable annual profits (revenue minus operating costs) over the life of the investment that depend on yields (Y tons per acre), output price (P dollars per ton), and variable costs (VC dollars per acre) such that the present value of the

[5] These assumptions about the yield-age profile and vine removal after twenty-five years are consistent with a "one-hoss shay" pattern of depreciation of the vine capital stock, which we use as an approximation to the true (but unknown) depreciation pattern that gives rise to the observed typical industry practice. In economics, the term "one-hoss shay" is used to describe a model of depreciation in which a durable product delivers the same flow of services throughout its lifetime until it fails instantaneously and has a scrap value of zero (see http://stats.oecd.org/glossary/detail.asp?ID=1904).

[6] Akiyama and Trivedi (1987) and Dorfman and Heien (1989) described modeling approaches based on neoclassical investment theory in which decisions to invest in new plantings are based explicitly on comparing the expected present value of future net income against the cost of the investment, rather than as some ad hoc function of past prices (see Gray et al., 2005).

returns to that investment is given by

$$PV_t = \sum_{n=0}^{T} (P_{t+n}Y_{t+n} - VC_{t+n})(1+r)^{-n}, \tag{1}$$

where PV_t is the present value in time t of net revenue generated by the investment in an acre of vines planted in time t, r is the real discount rate, and $T = 25$ is the lifespan of the vineyard investment.[7]

The optimal investment decision compares the present value of net income with the marginal cost of new plantings, $MC_t = C'(PL_t)$, which includes the costs of planting materials as well as labor, capital, and other inputs used to prepare the land and plant the vines. Then the (nonnegative) quantity of new plantings in each year t, chosen to maximize the net present value of the investment, will be the quantity of plantings such that present value of net returns per acre will be equal to the marginal cost of the new plantings per acre for that year:[8]

$$PV_t = C'(PL_t). \tag{2}$$

Bearing Acreage, Yield, and Production

Prices and net revenues over the life of the investment depend on future plantings as well as the current stock of vines and the current planting decision. To project these prices and revenues implicitly requires knowledge of the parameters on the supply side of the model—including yield relationships and the dynamics of the stock of bearing vines as well as the determinants of plantings—and on the demand side. Equations representing the biophysical and economic relationships that determine bearing acreage, costs of investment, yields, and production are developed next.

Vineyard acreage evolves according to

$$A_{a,t} = \begin{cases} PL_t & \text{for } a = 0 \\ A_{a-1,t-1} & \text{for } 1 \leq a \leq 25, \\ 0 & \text{for } a > 25 \end{cases} \tag{3}$$

where, in a given region in year t, PL_t represents plantings and $A_{a,t}$ is the acreage of vineyards currently a years old. Vines are lost to death from non-PD causes at a proportional rate of δ_0 and from PD at a proportional rate of δ_1; we assume these vines are replanted automatically every year unless they are twenty-three years of age or older.[9] Consequently, the age structure of the vines within a particular vineyard, initially planted a years in the past, changes over time depending on the rate of loss to PD. In turn, so does the average yield per acre.

Yield of mature vines in a given region is modeled as

$$YM_{t+n} = YM_t + gn, \tag{4}$$

where YM_{t+n} is the projected yield per mature bearing acre in year $t+n$, which is equal to the value in the previous year, YM_t, augmented by a linear growth rate g.[10] The average yield per acre aged

[7] In our application, values for n range from 0 to 25 because vines are removed after twenty-five years, and values for t range from 2011 to 2060 because we project investment decisions fifty years into the future.

[8] The optimal investment decision involves selecting a fifty-year time series of annual acreages of new plantings that maximizes profits over fifty years given exogenous anticipated prices. In the fiftieth year we project planting decisions out to year seventy-five, assuming a steady-state condition.

[9] Since vines take at least three years to bear commercial quantities, any replacement of these vines would not produce grapes before the entire block is removed at age twenty-five years.

[10] Initial yield, YM_0, is given in table A1. The underlying trend in yield per acre of mature vines reflects the influence of management and technological change (in reality, yields also reflect random seasonal variation in weather and pests that average out in this model, which emphasizes long-term investment responses). The trend growth rates and implied yield values in $t = 50$ were calibrated based on a combination of historical data; responses to a questionnaire sent to a group of winegrape growers, scientists, and industry experts; and some consultation within this group.

Table 2. High, Low, and Best-Guess Rates of PD Loss (δ_1) under Alternative Scenarios

	Baseline: With Current Policies and Technology			Outbreak: Without Current Policies		
Region	"High" Baseline PD Loss	"Low" Baseline PD Loss	Best Estimate Baseline PD Losses	"High" Outbreak PD Loss	"Low" Outbreak PD Loss	Best Estimate Outbreak PD Losses
	Vines lost to PD per 1,000 per year					
Napa-Sonoma	10	1	6	100	10	24
Coastal	2	0	1	5	0	4
Northern SJV	2	0	1	5	0	4
Southern SJV	8	0	2	40	8	15
S. California	10	2	4	90	40	40
N. California	0	0	0	0	0	0

Notes: "SJV" refers to the San Joaquin Valley.

a years in year $t+n$, $Y_{a,t+n}$, is also affected by the yield-age profile of vines and the age structure of the population of mature and immature bearing vines in that acre given the past replacement of vines lost to PD and other causes. Thus,

$$(5) \qquad Y_{a,t+n} = \left(\sum_{b=0}^{25} AA_{b,a} AY_b\right) YM_{t+n},$$

where $AA_{b,a}$ is the proportion of vines that are b years old in an acre that is a years old (note $b \leq a$) and AY_b is the yield per acre of vines b years old as a fraction of the yield of a mature vine.[11]

$$(6) \qquad AA_{b,a} = \begin{cases} 1 & a,\ b = 0 \\ \delta_0 + \delta_1 & 1 \leq a \leq 22,\ b = 0 \\ 0 & 23 \leq a \leq 25,\ b = 0 \\ 0 & a = 0,\ 1 \leq b \leq 25 \\ (1 - \delta_0 - \delta_1) AA_{a-1,b-1} & 1 \geq a,\ b \leq 25 \end{cases}$$

Values for the death-rate parameters δ_0 and δ_1 are based on advice from industry experts, and the critical PD death-rate parameter, δ_1, is subject to sensitivity analysis (see table 2).

The quantity of production is given by the product of the age-specific yield per acre from equation (5) and the corresponding number of acres from equation (3), summed across age categories:

$$(7) \qquad Q_{t+n} = \sum_{a=4}^{24} Y_{a,t+n} A_{a,t+n}.$$

Investment Cost for New Plantings and Replacement Plantings

Investment cost, C_t, is assumed to be a cubic function of the rate of new plantings, PL_t:

$$(8a) \qquad C_t = \mathrm{c}_1 PL_t + \mathrm{c}_2 PL_t^3.$$

The cubic form was chosen such that marginal cost would increase at an increasing rate, reflecting the fact that new plantings are constrained by the supply of planting material from the nursery

[11] In all regions, when an acre is first planted, $AY_b = 0$, whereas when that acre reaches maturity, $AY_b = 1$. Table B2 provides specific values for AY_b.

industry. Hence, the equations for the average and marginal cost of investment for new plantings are quadratic functions:

(8b) $$AC_t = \mathrm{c}_1 + \mathrm{c}_2 PL_t^2;$$

and

(8c) $$C'(PL_t) = MC_t = \mathrm{c}_1 + 3\mathrm{c}_2 PL_t^2.$$

These equations were parameterized using information on average costs taken from cost studies prepared by the UCCE (University of California Cooperative Extension, 2000–2011), CDFA/NASS Acreage Reports (National Agricultural Statistics Service, 1995–2012) and assumptions about the flexibility of supply of vine replacements (details in Appendix B).[12]

Substituting equation (8c) into equation (2) yields the quantity of plantings in each period t as implied by the present value of net revenues that will flow from new investment in that period given the anticipated prices and competitive market clearing:[13]

(9) $$PL_t^* = \sqrt{[(\widehat{PV}_t - \mathrm{c}_1)/3\mathrm{c}_2]}.$$

Variable Cost

The specification of the investment cost function in equation (8a) as a cubic form constrains the supply response to changes in price in the short run. In the Napa-Sonoma and Southern San Joaquin regions (but not in the other regions), variable costs are also an increasing function of the total region-wide vineyard acreage, reflecting the effects of upwards sloping supply of specialized inputs (in particular, high-quality land) to the winegrape industry in those regions; this is captured in the equation for land rent, R_{t+n}^i, in equation (B2). Variable costs also depend on the prevalence of PD in the region, which causes growers in regions with greater PD prevalence, such as Napa-Sonoma, the Southern San Joaquin Valley, and Southern California, to spend resources on preventive measures; other regions tend not to undertake preventive measures because PD pressure is relatively low in those areas.

Accordingly, in equation (10) average regional annual variable costs per acre differ according to (a) the age, b years, of the acre in question (the term $\mathrm{v}_{0,b}^i$), (b) different scenarios for the prevalence of PD in Napa-Sonoma, the Southern San Joaquin Valley, and Southern California (the term v_1^i)—d_i is a dummy variable that equals 1 if i is one of these three regions and 0 otherwise, (c) the cost of replanting vines lost to PD and other causes of death (RC_{t+n}^i), and (d) land rental rates, R_{t+n}^i, which depend on the total acreage of wine grapes within the region in Napa-Sonoma and southern San Joaquin (other regions have abundant land suitable for wine grapes).

(10) $$VC_{b,t+n}^i = \mathrm{v}_{0,b}^i + \mathrm{v}_1^i d_i + RC_{t+n}^i + R_{t+n}^i.$$

This equation is parameterized based on prior views about the elasticity of supply of vineyard land, regional acreage from Acreage Reports, and knowledge of the relationship between the sharpshooter population and the incidence of PD, gleaned from interviews with growers, scientists, and others who have expert knowledge about PD and its history throughout the state (California Department of Food and Agriculture/National Agricultural Statistics Service, 1981–2011). Details are provided in Appendices A and B.

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[12] Grapes are propagated vegetatively with scions grafted onto pest- and disease-resistant rootstocks. The supply of planting material itself entails perennial crop production with significant lags; nursery producers have to anticipate the mix of demand for combinations of rootstocks and scions for a range of different clones of each of many grape varieties.

[13] The same competitive market solutions can be derived equivalently by solving numerically for the profit-maximizing quantity of new plantings in each year, conditional on future prices for wine grapes, which are predetermined for each iteration of the model.

Demand for California Wine Grapes

The demand side of the model is represented by a system of linear inverse demand equations expressing prices for each of the three price-cum-quality winegrape categories ($i = Low$, *Medium*, or *High* price cum quality) as a function of the quantities of all three quality categories:

$$(11)\quad \begin{aligned} P_{Low,t} &= (\mathrm{h}_0^{Low} + \mathrm{m}_{Low}^{Low} Q_{Low,t} + \mathrm{m}_{Med}^{Low} Q_{Med,t} + \mathrm{m}_{High}^{Low} Q_{High,t})(1 + b^{Low})^t \\ P_{Med,t} &= (\mathrm{h}_0^{Med} + \mathrm{m}_{Low}^{Med} Q_{Low,t} + \mathrm{m}_{Med}^{Med} Q_{Med,t} + \mathrm{m}_{High}^{Med} Q_{High,t})(1 + b^{Med})^t \\ P_{High,t} &= (\mathrm{h}_0^{High} + \mathrm{m}_{Low}^{High} Q_{Low,t} + \mathrm{m}_{Med}^{High} Q_{Med,t} + \mathrm{m}_{High}^{High} Q_{High,t})(1 + b^{High})^t \end{aligned}$$

Values for the slope and intercept parameters for each of these equations were calculated using (a) the 2008–2010 three-year average values of prices and quantity for each region—based on data from the CDFA/NASS Crush Reports—combined with (b) estimates of price flexibilities, which were based primarily on the estimates reported by Fuller and Alston (2012) but with some adjustments during the process of calibrating the baseline model projections over fifty years to more closely conform to the results from survey questionnaires and comments by experts.[14] Values for the growth rate parameters, b^i in equation (11)—which reflect underlying growth rates in demand (reflecting the influence of growth in population, per capita income, and other trend factors)—were set at 0.3% per annum in each case in view of past trends in prices.

Model Closure and Solution Procedure

Each of the six regions in California is classified as producing one of three quality (or price) categories of wine grapes (see table 1). In any given year, production in each of the six regions, and thus of each of the three qualities, is predetermined by previous investment decisions. The model is closed by equating annual demand with annual supply for each of the three qualities of wine grapes and solving for the implied prices. We use an iterative procedure to solve numerically for the stream of plantings and the corresponding stream of prices that would be mutually consistent with the structure of the model, as described below.

Model Solution Procedure

We opted to impose a specific equilibrium concept that is consistent with all growers seeking to maximize the net present value of returns to new plantings, conditional on a rational prediction of the prices that this behavior would imply given the structure of the industry being modeled. To solve for this equilibrium such that the anticipated prices on which current (and future) investments are based is consistent with the market-clearing prices implied by those same investments, given the structure of the model, we adopt an iterative solution algorithm as introduced by Fair and Taylor (1983) and further developed by Miranda and Helmberger (1988).[15] In each iteration, numerical simulation

[14] The price flexibilities of demand for wine grapes are calibrated explicitly to reflect the fact that California wine grapes are used as an input in producing a final product (wine) that is traded internationally and competes in California, the rest of the United States, and elsewhere with wine from other U.S. states and other countries. Fuller and Alston (2012) discuss the nature of demand for California wine grapes and its determinants and the interpretation of the elasticities and flexibilities they estimated, using data on winegrape crush quantities and prices, as a basis for parameterizing the demand side of the simulation model presented here. The formulae for computing price slopes of the linear inverse demands from the corresponding price flexibilities, using the initial prices and quantities, are given in Appendix B.

[15] Gray et al. (2005) used the same equilibrium concept except that, given its stochastic elements, their application entailed rational expectations. We are not aware of any other models of perennial crops supply response that have used an equivalent equilibrium concept. Here we do not have any stochastic elements—although it would be straightforward to extend the model to include them—so we simply solve for the equilibrium values of the endogenous variables with exogenous variables and parameters all taking their (deterministic) expected values.

methods are used to solve for investments in plantings that maximize the present value of profits over the fifty years, given assumed values for future prices. In turn, these annual investments, combined with the starting values for age-specific acreage and the equations of the model, imply corresponding annual outcomes for production and prices over those fifty years.[16] This solution is conditional on the assumed values for future prices. In the next iteration, the solutions for prices just obtained are used as future prices and the process is repeated until a stable solution is achieved. Since the prices are exogenous for each iteration, the solution in every iteration is consistent with competitive price-taking behavior, but only the last iteration is also consistent with a rational prediction of those prices.

The solution process involves the following six steps for each policy scenario:

1. *Specify Parameters*. Values are specified for parameters in all of the equations in the model to represent the particular policy scenario and the production conditions to be modeled (as described in Appendices A and B).

2. *Specify Starting Values for Endogenous Variables*. Three-year (2009–2011) averages are used as a set of starting values for the future prices (2011–2061), which are combined with projected age-specific yields of vines (combining equations (4), (5), and (6)) to project the revenue over twenty-five years from plantings made for each of the fifty years between 2011 and 2060. Likewise, three-year (2009–2011) averages are used as starting values for the total acreage (2011–2061), which determines the land rents used in equation (10).

3. *Solve for Optimal Plantings, Conditional on Starting Values*. The information from the previous step is used in equation (1) to compute the present values of new plantings for each year of the simulation, which are then used in equation (9) to compute optimal plantings over the fifty years from 2011 to 2060.[17]

4. *Compute Outcomes Implied by Plantings*. The implied yearly numbers of vines by age category are used in equation (7), combined with the age-specific yield from equation (5) to compute quantities produced. The six region-specific quantities produced (each of which belongs to one of three quality categories) are aggregated into three quality-specific totals, which are substituted into the price-dependent system of demand equations, equation (11), to solve for the three quality-specific prices in each year of the simulation.

5. *Recompute the Present Values of Investment Based on the Model Solutions*. The prices and total acreage from the previous step are used to compute a new set of present values of variable profit over a twenty-five-year lifespan from new plantings for each year between 2011 and 2060. Those new present values are used to compute the corresponding optimal new plantings over those fifty years, conditional on the solutions for prices and total acreage from the previous iteration of the model.

6. *Iterate until Solutions Converge*. Projected plantings from step 5 are used as input into step 4. Steps 4 and 5 are repeated until the future prices used to generate plantings are equivalent to the prices implied by plantings.

Model Validation

Several steps were taken to check the validity of the model and its ability to predict winegrape market behavior over twenty-five or fifty years. Using initial values for parameters based on our own

[16] Specifically, we used the GAMS CONOPT solver, which is a nonlinear programming method that uses a generalized reduced gradient (GRG) algorithm based on the work of Abadie and Carpentier (1969).

[17] Plantings in year 2060 (the last year of the fifty-year period) depend on expected returns over the subsequent twenty-five years (2061 through 2085), and thus the fifty-year planning period entails projections over seventy-five years; solutions are found for the first fifty years and then the values are projected for the fiftieth year forward for the next twenty-five years as though a steady-state solution had been reached in year fifty.

knowledge and estimates, the model was calibrated and then used to simulate production quantities, acreage, prices, and the resulting profits, consumer surplus, and net benefits from 2011 to 2060. Relevant experts were then asked to review these predictions and comment on them as a check on whether the model as specified yielded plausible predictions. In an iterative, consultative process, parameters in the equations for demand, yield, flexibility of costs of new and replacement plantings, and PD damage were adjusted such that the predictions became more nearly in line with the expert opinions. Finally as a further check on the model, the implied region-specific supply elasticities were calculated by running parametric simulations. Long-run (thirty-year) own-price elasticities of region-specific supply are all between 0.8 and 4.7. Table B3 presents implied elasticities of supply of wine grapes over a range of time horizons. Figure 2 presents historical and model-predicted future values of the variables over time that were developed in the process described above using baseline parameter values.

Policy Simulations: Scenarios

Policy simulations were conducted under a range of assumptions about scenarios regarding potential cuts to program funding, PD prevalence, and a case in which the disease simply ceases to exist. Under each alternative scenario, producer benefits were computed for each year of the simulation as the change in profit or producer surplus (computed as an element of the model solution procedure) compared with the baseline scenario. Annual "consumer" benefits were computed as changes in Marshallian consumer surplus (the area behind each demand curve above the intersection of supply and demand), reflecting the effects of both price changes and shifts in demand. Annual total benefits are equal to the sum of producer and consumer benefits.

Much is unknown about the future of PD and the programs in place to keep it in check. Potential changes to disease pressure may occur because of climate change, new vectors, movement of existing vectors to new locations, different cropping patterns, new technologies, urbanization, or changes to government programs. PD programs may be altered because of budget shortages, competition from other pests and diseases for policy resources, changes to administration, or for other reasons. We created several scenarios to address these possibilities.

We consulted industry experts to enable us to make more confident predictions of likely pest and disease prevalence and industry growth under alternative scenarios. Expert opinions on the potential future of disease incidence and winegrape production in California were elicited in both informal consultations and through the use of a questionnaire that was sent to various experts, including winegrape growers, academics, and farm advisors. We used questionnaire results, sensitivity analysis, and subsequent discussions with relevant experts about the implications of the parameter values to choose "best-estimate" values for all parameters. For the PD death-rate parameter, δ_1, we used the range of values provided by respondents in the sensitivity analysis presented below (see table 2 for details.)

Baseline

The "baseline" scenario represents economic outcomes given the current programs, technology, disease incidence, and mitigation practices. Under this scenario, the myriad CDFA-, USDA-, and locally funded Pierce's Disease boards, task forces, and monitoring and control programs remain in place for the seventy-five-year period being analyzed.

Silver Bullet

The best possible (although extremely unlikely) outcome of the PD research program would be a costless cure, or "silver bullet," for PD. The death rate of vines is simply reduced in the model to

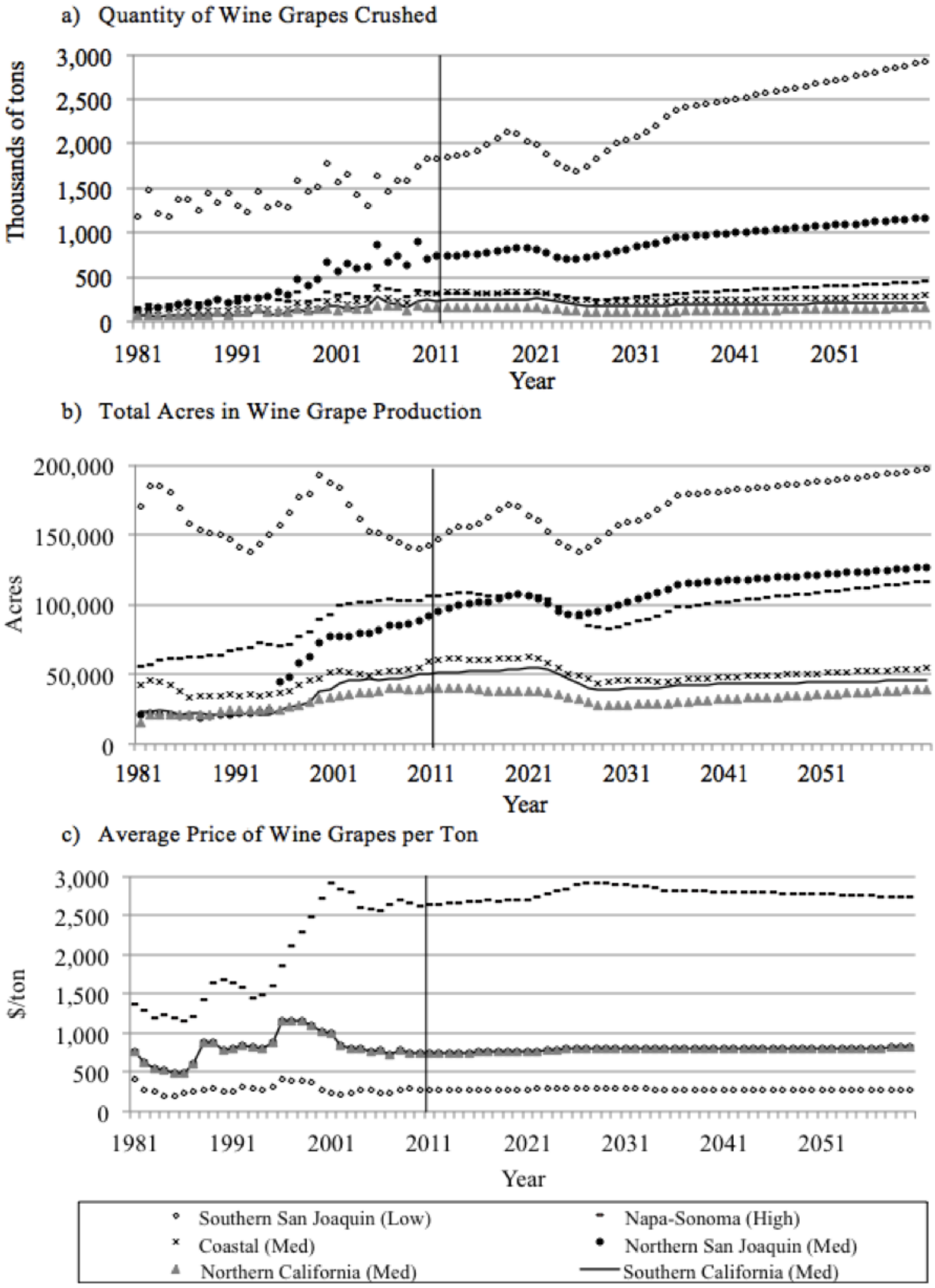

Figure 2. Historical (1981–2010) and Baseline Model Output (2011–2060)

what it would be in the absence of PD: δ_1 in equation (6) and PD mitigation costs are set to zero. The difference in economic welfare between the baseline case and the "silver bullet" scenario can be interpreted as the cost (or benefit) of PD as borne by winegrape producers and consumers under current policies and technology.[18]

Statewide Outbreak

The worst potential scenario is a statewide "outbreak" in which GWSSs are free to move and become established throughout California. It is possible that this could eventually occur even with the current programs in place, and many experts say they believe that GWSSs would almost certainly become endemic throughout California if the control programs ended. It could take a long time for the full consequences of ending the program to be realized. In the questionnaire, respondents were asked what would happen in terms of the eventual equilibrium distribution of annual losses of vines from PD if the PD Control Program ended. Based on the survey responses, it takes ten years in the model before the full effect (higher rates of vine losses) from a widespread outbreak is felt.

In this outbreak scenario, PD pressure increases in all regions except for Northern California, which is generally considered too cold for both the disease and its vectors. All other regions experience a proportional increase in PD incidence, resulting from either an increase in the existing presence or a new introduction of GWSSs, with southern San Joaquin and Napa-Sonoma faring the worst. Both of those regions begin with a higher PD incidence than the other areas; additionally, the proportional increase in PD in southern San Joaquin is expected to be very large if the program ends. The rate of PD deaths, used in equation (6), is assumed to grow exponentially between the baseline rate (δ_1 at $t = 0$, for 2010) and the full outbreak disease incidence (δ_1 at $t = 10$, for 2020). Table 2 provides region-specific PD-induced death rates under the baseline and outbreak scenarios based on survey responses.

Regional Outbreaks

Alternative outbreak scenarios in which GWSSs become endemic in particular regions in isolation are also considered. If the pesticides used in Southern California became ineffective, GWSS and PD prevalence could increase in that region alone. Alternatively, if programs aimed at limiting the spread of GWSS from Southern California were eliminated or cut back, the southern San Joaquin Valley could experience outbreak rates of PD losses. The biggest fear, however, is that GWSSs could migrate into the Napa and Sonoma Valleys and become established in that high-value region in addition to BGSSs, which are already a problem there. The regional outbreak scenarios use baseline PD incidence rates for all regions except the one with the outbreak, for which PD incidence is set to the corresponding "outbreak" rates (which are also used together to represent a statewide outbreak rate).

Policy Simulations: Results

Table 3 shows changes in welfare under the various scenarios described in the previous section relative to the baseline case. These changes are the simple averages of the annual welfare changes from 2011 to 2060. These were computed by averaging the annual welfare measures over fifty years for each region and for the state as a whole, without any discounting. While the simulation is

[18] Our analysis of the "silver bullet" scenario does not take into account potentially negative economic impacts that a costless cure for PD could have on California grape producers. If such a cure were found, large-scale grape production might become possible in other parts of the country (or other countries) that currently cannot produce grapes because of high PD incidence and a lack of effective prevention tools (Anderson, Crocker, and Mortensen, 2011; Hopkins and Purcell, 2002). Increased production, all else equal, would bring grape prices down, which would negatively affect California winegrape growers. For the purposes of this analysis, we therefore assume that the "silver bullet" is a California-specific cure.

based on the net present value of returns to investments over the life of the vineyard, we present the annual averages of the undiscounted welfare measures to provide estimates that are more easily and intuitively compared to other annual measures such as program expenditures and value of production.

The measured welfare changes represent changes in producer and consumer surplus for producers and consumers of wine grapes. They do not include the costs of government expenditure (effectively borne by taxpayers) or costs (or benefits) to the citrus industry or nursery industry associated with the current PD control program and compliance with it. The first six columns in table 3 present regional effects, and the rightmost column shows the statewide sum. The "net benefit" within a region should not be interpreted as a measure of net benefits to that region but rather is a measure of net benefits to producers and consumers (or buyers) of the wine grapes from that region. Some of the "consumer" benefits will accrue to winemakers in the same region, but a large part of the "consumer" benefits will accrue to final consumers in other geographical locations, possibly outside California.

The first section of table 3 reports results from the "silver bullet" scenario as compared to the baseline, a measure of the costs of the disease to producers and consumers given current programs. The results for the "silver bullet" case suggest that the disease costs producers and consumers of California wine grapes over $92 million per year.[19] More than half of this cost, $64 million or roughly 2.9% of winegrape cash income in recent years (California Department of Food and Agriculture and USDA National Agricultural Statistics Service, 2011), is borne by producers in California.[20] These statewide benefits from eliminating PD are net of the losses borne by producers in Northern California, where savings of PD costs would be comparatively minor and more than offset by the effects of lower prices resulting from the increased production in other areas.

In the statewide outbreak scenario the state as a whole is projected to lose over $185 million annually compared to the baseline, including a loss to producers of $126 million per year, or 5.7% of winegrape cash income in recent years. This total reflects the effects net of benefits to growers in Northern California, where there is no PD. In these regions, PD costs would be comparatively minor and more than offset by the benefits of higher prices resulting from the heavier losses in the primary production areas.

The statewide annual cost of regional outbreaks compared to the baseline is $77 million for Napa-Sonoma, $47 million for the southern San Joaquin Valley, and $44 million for Southern California. Projected losses are very dire for some regions, in particular for Napa-Sonoma and Southern California, both of which experience drastic increases in PD from a regional outbreak. Regional outbreaks benefit producers in the regions that are not affected directly because of price increases resulting from a lower total statewide grape crush. A Napa-Sonoma-only outbreak, for example, would benefit all producers except those in the Napa-Sonoma region. However, the corresponding losses to consumers resulting from increased prices would more than offset the producer gains for each of those other regions. The statewide effects for producers, consumers, and their combined sum are all negative.

Because the sum of the change from "silver bullet" to "baseline" and "baseline" to "outbreak" is equivalent to the difference between "silver bullet" and "outbreak," the welfare effects of alternative scenarios as compared to a scenario with no PD can be computed. As such, relative to a scenario

[19] Tumber, Alston, and Fuller (2013) estimated the total cost of losses from PD to producers as $56 billion per year in 2010 using generally similar data and assumptions. This is an estimate of the initial incidence of the total cost, some of which would be shifted to consumers through induced increases in winegrape prices. It is conceptually comparable to the total cost to producers and consumers reported here, except that the $92 million is an average value over the fifty years between 2011 and 2060, and it reflects considerable growth in the scale of the industry over that half century and thus in the scale of annual losses. It also reflects various other differences in details, including some differences in assumptions about PD incidence and the fact that costs of land rental and planting material, which are endogenous in the analysis here, are treated as fixed by Tumber, Alston, and Fuller (2013).

[20] As noted, this measure does not include the costs of the PD program, borne by government and industry, but not reflected in the market for wine grapes.

Table 3. Average Annual Welfare Changes, Relative to "Best-Estimate" Baseline, Undiscounted Values

	Napa-Sonoma	Coastal	Northern San Joaquin	Northern California	Southern California	Southern San Joaquin	State Total Wine Grapes
				$ thousands per year			
Silver Bullet							
Producer Surplus	26,804	714	387	−540	12,689	23,992	64,046
Consumer Surplus	15,449	858	3,189	402	690	7,395	27,983
Net Benefit	42,253	1,572	3,576	−138	13,379	31,387	92,029
Statewide Outbreak							
Producer Surplus	−47,437	−1,635	−958	1,668	−43,948	−34,164	−126,474
Consumer Surplus	−30,095	−2,563	−9,756	−1,268	−1,652	−13,652	−58,987
Net Benefit	−77,533	−4,198	−10,713	400	−45,600	−47,816	−185,460
Napa-Sonoma Outbreak							
Producer Surplus	−47,507	759	2,660	412	563	1,483	−41,630
Consumer Surplus	−29,982	−654	−2,466	−312	−507	−1,697	−35,618
Net Benefit	−77,489	105	194	99	56	−213	−77,248
Southern San Joaquin Valley Outbreak							
Producer Surplus	14	40	140	22	30	−35,787	−35,542
Consumer Surplus	−19	−34	−129	−16	−27	−11,515	−11,740
Net Benefit	−6	6	11	5	3	−47,301	−47,282
Southern California Outbreak							
Producer Surplus	50	1,569	5,459	853	−44,285	300	−36,054
Consumer Surplus	−69	−1,343	−5,035	−642	−846	−339	−8,272
Net Benefit	−19	226	424	212	−45,131	−39	−44,327

Table 4. Average Annual Welfare Changes, Relative to Alternative Baselines, Undiscounted Values

	Napa-Sonoma	Coastal	Northern SJV	Northern California	Southern California	Southern SJV	State Total Wine Grapes
	$ thousands per year						
Silver Bullet							
High Baseline	61,555	3,196	7,340	−237	21,913	53,379	147,146
Best Estimate Baseline	42,253	1,572	3,576	−138	13,379	31,387	92,029
Low Baseline	17,949	−64	−121	−60	10,660	24,640	53,004
Statewide Outbreak							
High Baseline	−58,232	−2,564	−6,937	301	−37,084	−25,789	−130,306
Best Estimate Baseline	−77,533	−4,198	−10,713	400	−45,600	−47,816	−185,460
Low Baseline	−101,839	−5,849	−14,429	479	−48,264	−54,544	−224,446

Notes: The net benefit is the sum of changes in consumer and producer surplus relative to the baseline. (Results for the "silver bullet" and the "statewide outbreak" relative to the "best-estimate" baseline are also presented in Table 3.) "High" and "low" refer to the upper and lower bounds on the estimated rates of PD losses in the baseline scenario (i.e., with the current policy in place). "SJV" refers to the San Joaquin Valley.

without PD, the full cost of a statewide outbreak could be in the range of $280 million annually (i.e., $185 million for the cost of the outbreak compared with the status quo and a further $92 million for the cost of the status quo compared to a scenario with no PD).[21]

Sensitivity Analysis

Because much is unknown about current and potential incidence of PD, we examined the range of economic impacts of the disease implied by the range of rates of incidence indicated by the survey responses. We applied the full range of questionnaire responses on rates of incidence to parameterize scenarios for current PD losses as well as potential losses if the program were abolished.

Table 4 compares average annual changes in total welfare over fifty years for both the statewide "outbreak" scenario and the "silver bullet" scenario compared with the "baseline" scenario using three alternative parameterizations of the "baseline" scenario ("low," "high," or "best-estimate" rates of losses to PD). "High" indicates the maximum value for baseline PD losses from the survey responses and "low" represents the minimum. The relatively modest range of baseline rates of losses to PD implies substantial differences in estimated welfare impacts. The net welfare effect for California wine grapes as a whole ranges from $53 million to $147 million per year. Each regional measure varies by more than a factor of two, which is substantial and highlights the importance of good parameter estimates and the difficulties of making confident, precise statements about costs of PD. The remainder of table 4 compares a statewide outbreak to the range of PD baselines. The estimated average annual cost of a statewide outbreak to California winegrape producers and consumers ranges from $130 million to $224 million.

The analysis in table 4 holds constant the expected prevalence of PD in the "outbreak" scenario and varies the prevalence in the "baseline" with the current program in place. Further analysis was conducted to explore the sensitivity of findings to assumptions about PD prevalence in the statewide "outbreak" scenario—as would apply if the PD program were to end—holding constant the "baseline" prevalence at the "best-estimate" rates. Survey responses varied widely regarding what could happen if the PD program ended. Using the range of PD losses suggested in surveys

[21] These costs refer to the producers and consumers of wine grapes (the focus of this paper) and not producers of other grape products or other industries affected by PD and the PD Control Program. We do not formally evaluate the costs of PD borne by producers and consumers of grapes used for other purposes (table grapes, raisins, or grape juice). However, using an approximation approach we estimated that allowing for effects in these industries would increase the costs of a statewide outbreak by about 30%, with those impacts being concentrated in the southern San Joaquin Valley, where raisin and table grapes are produced.

Table 5. Average Annual Welfare Changes, Relative to "Best-Estimate" Baseline

	Best Estimate Outbreak Losses			High Outbreak Losses	Low Outbreak Losses
Region	**Producer Surplus**	**Consumer Surplus**	**Net Benefit**	**Net Benefit**	**Net Benefit**
Napa-Sonoma	−47,437	−30,095	−77,533	−306,061	−17,780
Coastal	−1,635	−2,563	−4,198	−5,190	1,702
Northern San Joaquin	−958	−9,756	−10,713	−13,669	−10,272
Northern California	1,668	−1,268	400	1,084	270
Southern California	−43,948	−1,652	−45,600	−77,285	−45,283
Southern San Joaquin	−34,164	−13,652	−47,816	−193,232	−193,232
State Total Wine Grapes	−126,474	−58,987	−185,460	−594,353	−91,692

Notes: The net benefit is the sum of changes in consumer and producer surplus relative to the "best-estimate" baseline. Figures in parentheses below the net benefits are percentage differences between the estimate (i.e., "high" or "low" rates of outbreak losses to PD) and the corresponding estimate using "best-estimate" rates of outbreak losses to PD.

for the "outbreak" scenario to parameterize the model (see results labeled "low outbreak" and "high outbreak" in table 5), the estimated prospective welfare losses range from \$92 to \$594 million per year (these are undiscounted values).

Caveats and Limitations

The results reported here refer to economic outcomes over a fifty year future period that was projected using a model of the impact of a relatively new exotic pest as it affects one of the most challenging of agricultural industries to model, a perennial crop industry producing a highly differentiated product. This context calls for a calibrated model, and it is not easy to directly validate most (if not all) of the individual parameters, especially as they are applied to the more distant future. Further, in this instance, much of the science of the pest and disease problem and its implications is in its infancy and incomplete. The task of the modeler in such a context becomes one of obtaining the best possible estimates of the key parameters and conducting sensitivity analyses around those parameters that are thought to be most critical or for which the likely values are most uncertain. In many instances these estimates will be subjective or based on opinions, with only a partial scientific or statistical basis.

Our model parameterization comprises two main steps. The first step was the baseline parameterization, which entailed region-specific parameterization of (a) yield functions (including growth rates over time), (b) land supply functions and cost functions of new plantings, which together determined the short- and long-run supply-response elasticities, (c) the rate of loss to PD given current policy, and (d) the demand side of the model. Initial parameterization of the yield functions was based on a mixture of data and subjective opinions, including a review of past trends, some experimentation with time-series models, and consultation with industry experts given prior views about the likely maximum yields to be achieved over a fifty-year period of linear growth. Initial parameterization of the demand side of the model was based on the estimates from Fuller and Alston (2012) with some modest adjustment based on advice from experts on the nature of demand for wine grapes. Because there is little hard data available, initial assumed rates of loss to PD were based on advice from entomologists, plant pathologists, growers, and other industry experts.[22]

To "validate" the baseline parameterization, we reviewed the implied time paths of acreage, production, and prices for the six regions over the fifty-year period, and to "correct" those projections

[22] A referee raised the possibility that respondents were interested parties and may have given biased estimates. We were conscious of this possibility. Our respondents included some who strongly supported the PD program and others who were very skeptical about whether it was worthwhile. These attitudes may have reflected biases, which may have been reflected in their responses to our questionnaire, but it is hard to separate "bias" from other sources of differences of opinion in settings of this nature. Such different perceptions surely contributed to the range in estimated parameters for PD incidence, but we have no way of knowing whether the "most likely" values were biased up or down as a result.

adjusted the parameters in the equations for the cost functions for new plantings and the elasticity of supply of land for wine grapes. We had to choose which of several parameters to adjust to move the projected variables in the desired directions. It was an empirical process, and we could not be sure if we were moving the trends in the right direction (the future of the industry remains unknown to us) or if we were adjusting the right parameters, or that the solution is unique—alternative combinations of parameter values might have yielded similar patterns of results. At the end of this process, however, we had a set of parameters that yielded projected prices, acreage, yields, and production that were considered reasonably plausible by a consensus of experts whom we consulted; the implied supply elasticities are also plausible and consistent with other evidence in the literature (e.g., Volpe et al., 2010).

The second step was a set of alternative parameterizations with respect to the prevalence of PD and the consequent rates of vine loss, developed to reflect the implications of alternative policy scenarios, or to demonstrate the sensitivity of results to departures from the baseline scenario. Because we expected them to be crucial determinants of the results, and because their values are particularly uncertain, we focused our sensitivity analysis on these parameters.[23] To be sure, the estimates of prevalence are subjective and subject to considerable uncertainty, as reflected in the range of responses to our questionnaires. As our results show, our findings are very sensitive to these prevalence parameters, and the precision of the results would be much improved if uncertainty about these parameters could be reduced. How that could be achieved is not clear.

Conclusion

Tumber, Alston, and Fuller (2013) estimated costs of the current Pierce's Disease program borne by taxpayers, citrus producers, and plant nurseries; costs to the wine industry from lost production; and costs of replacing vines lost to the disease under the existing program. The simulations and associated welfare calculations presented in this paper build on that work and provide a more complete set of measures of the total costs of PD as borne by the winegrape industry with or without the PD program as well as the economic incidence between winegrape consumers and producers, region by region.

This simulation model uses parameters that characterize investment and production response to changes in prices and returns many decades into the future in a comparatively detailed representation of the structure of production that was designed to capture the particular features of the pest-cum-disease problem that destroys healthy grapevines. To calibrate such a model necessarily relies on judgment by the modeler. We took considerable pains to draw as much as possible on advice from experts knowledgeable about the industry and its prospects and the region-specific implications of PD/GWSS and programs to manage it. Most elements of the model and most of the parameters were defined using detailed information about the technology and costs of production and based on previous models of demand and production. Even so, some subjective judgment was unavoidably involved.

While we were guided in these decisions by analysis of the implications for the baseline projections and discussions with experts, there is no way to "test" or "validate" these detailed parameterization choices, which are meant to characterize production and markets a half century and more into the future. The key sources of relevant uncertainty here are the parameters that represent

[23] In a similar context, Alston, Norton, and Pardey (1998)—following Griliches (1958)—suggested that a first approximation to gross annual research benefits (GARB) would be given by $GARB = kV_0$, where k is the proportional research-induced saving in costs per unit of production and V_0 represents the baseline value of production. In the present context, V_0 corresponds to the value of winegrape production in the baseline scenario and k represents the benefit (as a proportion of revenue) resulting from a reduction in PD prevalence. Our high baseline rates of PD prevalence are five to ten times higher than our low baseline rates, reflecting our uncertainty about this parameter. Our baseline projections of the price, quantity, and value of wine grape production are subject to much less uncertainty (we have narrower prior distributions for these variables) and consequently are much less important as a source of uncertainty about the implications of our work.

rates of vine loss to PD over the projected half century, both under the current policy and under alternative policies. Therefore, we focused our sensitivity analysis on these parameters.

The results of the simulations using our "best estimates" suggest that programs in place to curb PD yield a net economic benefit. All of the questionnaire respondents stated that they thought PD incidence would increase if the programs were halted, and the simulation results suggest that the annual economic benefit from the program remaining in place is greater than the costs of running the program: the program currently costs approximately $47 million per year Tumber, Alston, and Fuller (2013), while the annual cost of the "most likely" outbreak scenario resulting from cessation of the PD program is nearly four times that amount (i.e., $185 million per year as shown in table 3)—an approximate benefit-cost ratio of roughly 4:1. The savings and benefit-cost ratio are substantial even though the yearly average of benefits from the program includes the first ten years (in which losses from PD incidence are building to outbreak rates but have not yet reached them) and the fact that producers in some less-affected regions may be better off in the outbreak scenario because of increased prices resulting from disease-induced reductions in supply from more affected regions.

The sensitivity analysis suggests that the program yields net benefits, even under the most conservative assumptions. Using the "high" end of responses regarding potential PD incidence if program funding were cut, the program is estimated to yield annual benefits of up to $595 million compared with a scenario where the program does not exist. Using "low" rates of annual losses to PD, the annual cost to the winegrape industry from eliminating the program would be $92 million (see table 5); even under the "low" outbreak scenario and after program costs are taken into account, the program is still expected to yield net benefits. These estimates do not include the substantial potential benefits to the table grape and raisin grape industries, which would imply scaling up the measures of benefits by 30% or so, depending on the specific scenario being evaluated.

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Appendix A: Questionnaire

A questionnaire was sent to twenty-eight individuals in late January 2012. Two versions of the questionnaire were drafted. The first survey was constructed to gain feedback from individuals who would be knowledgeable mainly about the likely future of the disease in different areas of the state. This survey centered on questions about current and future PD incidence rates in the six different regions of the state, as defined in table 1 and figure 1, both under current policy and if current programs were eliminated. The second survey was a longer version that asked the same questions about disease incidence as well as questions about future winegrape production—regional yields, quantity produced, and acreage—to be used, in part, to parameterize the "baseline" model. Two reminders were sent to nonresponsive individuals.

Seven of twelve individuals who received the long version of the survey responded, an approximately 58% response rate. Eight of seventeen individuals who received the short form of the survey responded, a 47% response rate. The surveys were sent to individuals considered to be Pierce's Disease experts, including academic and government researchers, winemakers, farm advisors, vineyard managers, and pest control advisors. Responses were received from at least one individual from each group. Of the individuals who responded, many did not answer all of the questions, but only answered specific questions for region(s) with which they were most familiar. Many indicated they were hesitant to make what they saw as guesses about future events. Nonetheless, the responses that were received were helpful in formulating both relevant ranges and best estimates for baseline projections and scenarios.

Table A1 includes a summary of survey results and the resulting baseline model parameters for future production. The "initial" values for yield, acreage, production, and price were calculated as regional averages weighted by tons crushed and averaged again over 2008–2010 using Crush and Acreage Report data from CDFA/NASS. Parameters defining the initial region-specific yield and its growth rate must be specified by the model user, so both the initial and fifty-year values are the results of these specifications. Likewise, parameters representing annual region-specific loss-rates to PD must be specified in the model. Future acreage and quantity produced are variables, the values of which are determined within the model. For each region, the last row in each section of table A1 shows values for yield, bearing acreage, and production in 2061 (fifty years out).

Table A1 presents results from the long version of the survey only; this table shows the survey responses and the corresponding parameterizations or implied values for future production. The first section deals with yields (tons of grapes produced per acre). In general, there was consensus among respondents that yields would increase over time, although some individuals said they thought yields would remain constant for some of the regions. The yields in 2061 that were chosen reflect an upward trend in yields that is stronger in some regions than in others. The southern San Joaquin Valley, which currently has the highest yields (14.6 tons per acre), remains the highest yielding region after fifty years, with a model assumption of 18.2 tons per acre in 2061. Napa-Sonoma, which begins as the lowest-yielding (3.4 tons per acre) region in California, remains the lowest-yielding region after fifty years, with 5.0 tons per acre.

Most respondents said that in the fifty-year time period they expected acreage to increase substantially in all regions except Napa-Sonoma, where almost all suitable vineyard land is already in use. The model results produce acreages in fifty years that are largely in line with (or near) the range of survey responses. The model acreage in Napa-Sonoma expands approximately 17%, or 17,000 acres, which seems feasible over that time frame.

Production also increases in all regions, reflecting a combination of larger yields and acreages. Most respondents reported that they expected production in Napa-Sonoma to increase; the model reflects this, although not to the extent suggested by respondents. Because vineyard acreage is

Table A1. Summary of Questionnaire Results: Future Production

	Napa-Sonoma	Coastal	Northern San Joaquin Valley	Southern San Joaquin Valley	Southern California	Northern California
Yield (*tons/acre*)						
Initial Yield	3.4	6.4	8.9	14.6	5.7	4.7
Survey Response Ranges, Year 50	3.4–7.2	7.1–10.0	9.8–15.0	13.0–25.0	5.7–10.0	5.2–10.0
Number of Responses	5	4	4	4	3	2
Yield, Year 50	5.0	7.1	11.1	18.2	6.3	5.2
Acreage (*1,000 bearing acres*)						
Initial Acreage	99.7	51.4	82.4	133.3	45.9	37.2
Survey Response Ranges, Year 50	99.7*	51.4–73.9	82.4–132.7	133.3–208.1	45.9–60.0	37.2–50.0
Number of Responses	5	4	4	4	3	2
Acreage, Year 50	107.6	70.2	123.9	181.5	71.2	56.8
Production (*1,000 tons*)						
Initial Production	323.5	281.2	746.3	1,715.6	208.8	152.7
Survey Response Ranges, Year 25	340.0	281.2	746.3	1,715.6	208.8	
Survey Response Ranges, Year 50	511.2–734.1	399.3–738.7	1,676.5–2,032.9	4,000.0*	600.0*	500.0*
Number of Responses	4	4	4	3	3	1
Production, Year 50	414.3	375.4	1,133.8	2,675.4	331.1	228.6

Notes: Yield refers to yield of mature, fully bearing vines. Vineyards typically have a mix of nonbearing vines, vines that are bearing but not yet bearing at their eventual maximum yield, and fully bearing vines. Acreage and production take into account all bearing vines. However, some of these are not yet bearing at their maximum and so the product of yield (of mature vines) and bearing acreage is greater than production as shown in this table. Single asterisks (*) indicate that survey respondents did not provide any other suggestions.

Table A2. Summary of Questionnaire Results

Region	With Current Policies (Baseline)			Without Current Policies (Outbreak)		
	Suggested PD Losses after 10–20 Yrs	No. of Responses	Best-Estimate PD Losses	Suggested PD Losses after 10–20 Yrs	No. of Responses	Best-Estimate PD Losses
	(*Vines/1,000*)		(*Vines/1,000*)	(*Vines/1,000*)		(*Vines/1,000*)
Napa-Sonoma	1–10	10	6	10–100	6	24
Coastal	0–2	6	1	0–5	4	4
Northern SJV	0–2	6	1	0–5	5	4
Southern SJV	0–8	7	2	8–40	5	15
S. California	2–10	5	4	40–90	4	40
N. California	0*	4	0	0	4	0*

Notes: Single asterisks (*) indicate that survey respondents did not provide any other suggestions. "SJV" refers to the San Joaquin Valley.

limited and yields in Napa are likely to remain quite low relative to other regions (this was generally agreed upon by respondents), the very high production suggested is not feasible.[24]

Table A2 reports survey results about current and future PD-related losses of vines from both the short and long survey versions. Respondents offered wide-ranging and often conflicting opinions regarding PD incidence, both under the current program and if programs ceased to exist. This questionnaire asked about average vine deaths per 1,000 resulting from PD over the next 10–20 years. In general, respondents concurred that PD losses are very small in the Coastal, Northern California, northern San Joaquin Valley, and southern San Joaquin Valley regions.[25] Napa-Sonoma and Southern California are hotspots, with estimates of between one and ten vines per 1,000 dying annually in these regions. Ranges were even wider regarding potential losses if the current PD program were ended: some respondents thought that losses would remain the same as at present, while others estimated that losses would rise to roughly 100 vines per 1,000 annually in Napa-Sonoma and Southern California. Respondents thought that the baseline rates of PD losses in a no-policy scenario would remain at zero in Northern California, relatively low in the Coastal region and the northern San Joaquin Valley, and higher in the southern San Joaquin Valley, Southern California, and Napa-Sonoma. Specific estimates of likely loss rates varied among respondents, though they ranked the regions similarly.

[24] There may have been some confusion regarding the time horizon in this question. Only one person responded regarding production over the twenty-five-year time frame that the survey asked about, although several others indicated that production numbers could be calculated from yield and acreage responses, which were over a fifty-year time horizon.

[25] Some isolated areas of Santa Cruz county were reported to have Pierce's Disease problems, but the PD in these areas has not spread over time, and that county produces only very small amounts of grapes.

Table A3. Baseline Model Parameters

Parameter	Interpretation	Region	Value	Source
r	Discount rate	5% per year for all regions		
g	Yield growth rate per year as a percentage of initial yield	Napa-Sonoma	0.9%	Questionnaire and subsequent follow-up meetings with experts
		Coastal	0.2%	
		Northern SJV	0.5%	
		Southern SJV	0.5%	
		S. California	0.2%	
		N. California	0.2%	
Planting cost elasticities	Used to calculate the planting costs, c_1–c_4	Napa-Sonoma	15.75	Calibration of model results to expert prediction
		Coastal	3	
		Northern SJV	2	
		Southern SJV	2.75	
		S. California	2	
		N. California	6.75	
AC_0	Average per acre cost of new planting implicit in equations (8a)–(8c) ($/acre)	Napa-Sonoma	3,723	UCCE cost studies
		Coastal	16,956	
		Northern SJV	7,685.62	
		Southern SJV	6,061.3	
		S. California	7,325.01	
		N. California	7,843	
c_1	Unit cost coefficient in planting cost equations (8a)–(8c)	Napa-Sonoma	16,250	Planting cost elasticities, UCCE cost studies used for average costs
		Coastal	6,405	
		Northern SJV	4,546	
		Southern SJV	3,046	
		S. California	5,882	
		N. California	6,782	
c_2	Cubic cost coefficient in plantings cost equations (8a)–(8c)	Napa-Sonoma	0.0012	Planting cost elasticities, UCCE cost studies used for average costs
		Coastal	0.0011	
		Northern SJV	0.0010	
		Southern SJV	0.0002	
		S. California	0.0027	
		N. California	0.0011	
δ_0	Assumed acres lost by natural death	1% per year for all regions		Interviews with growers, expert opinion
δ_1	Assumed acres lost to PD (baseline)	Napa-Sonoma	0.6%	Questionnaire and subsequent follow-up meetings with experts
		Coastal	0.1%	
		Northern SJV	0.1%	
		Southern SJV	0.2%	
		S. California	0.4%	
		N. California	0.0%	

Table A3. – continued from previous page

Parameter	Interpretation	Region	Value	Source
RAC_0	Average per acre cost of replacement vines implicit in equation (B3) ($/acre)	Napa-Sonoma	5,092	UCCE cost studies
		Coastal	18,689	
		Northern SJV	8,682	
		Southern SJV	6,126	
		S. California	8,437	
		N. California	8,789	
c_3	Unit cost coefficient in vine replacement cost equation (B3)	Napa-Sonoma	17,910	Planting cost elasticities, UCCE cost studies
		Coastal	7,235	
		Northern SJV	4,595	
		Southern SJV	4,166	
		S. California	6,592	
		N. California	7,812	
c_4	Quadratic cost coefficient in vine replacement cost equation (B3)	Napa-Sonoma	0.0003	Planting cost elasticities, UCCE cost studies
		Coastal	0.0042	
		Northern SJV	0.0018	
		Southern SJV	0.0004	
		S. California	0.0050	
		N. California	0.0044	
$v^i_{0,b}$	Variable cost based on vineyard age from equation (10)	See table B3 for specific numbers.		UCCE cost studies
v^i_1	PD mitigation cost from equation (10)	$150 per acre in Napa-Sonoma, Southern SJV, and S. California $0 elsewhere		Grower interviews
R_0	Intercept in land rent equation (B4)	Napa-Sonoma	−1,300	Calibrated to equilibrium land rent value
		Coastal	350	
		Northern SJV	125	
		Southern SJV	−300	
		S. California	150	
		N. California	100	
R_1	Slope coefficient land rent equation (B4)	Napa-Sonoma	0.025	Calibrated to equilibrium land rent value
		Coastal	0	
		Northern SJV	0	
		Southern SJV	0.004	
		S. California	0	
		N. California	0	

Table A3. – continued from previous page

Parameter	Interpretation	Region	Value	Source
Equilibrium land rent value		Napa-Sonoma	1,300	Land rent equation; ranges from CCASFMRA (2012); calibrated to expert opinion on patterns of acreage
		Coastal	350	
		Northern SJV	125	
		Southern SJV	300	
		S. California	150	
		N. California	100	
Elasticity of land supply		Napa-Sonoma	0.5	Calibrated to expert opinion on patterns of acreage
		Coastal	1,000,000	
		Northern SJV	1,000,000	
		Southern SJV	0.5	
		S. California	1,000,000	
		N. California	1,000,000	

Notes: "SJV" refers to the San Joaquin Valley.

Appendix B: Parameterization of the Model

Demand

Equation (11) provides the demand system used in the model. Estimates of demand flexibilities were obtained from Fuller and Alston (2012). The initial region-specific price and quantity of wine grapes ($\overline{p}^i$ and $\overline{q}^i$ in table B1) were computed using the 2008–2010 averages of values from CDFA/NASS Crush Reports. The slope parameters for each region, m^i_j, were computed as the flexibility multiplied by the ratio of the initial price to initial quantity for each quality class. The intercepts were then constructed by substituting the initial quantities and prices into the demand model and solving for the intercepts, h^i_0, by setting each row of equation (11) equal to zero and substituting $\overline{q}_j$ for $Q_{j,t}$, which yields

$$\text{(B1)} \qquad \mathrm{h}^i_0 = \sum_j \mathrm{m}^i_j \overline{q}_j,$$

where i represents the quality category in question and j can represent Low, Medium, or High quality. We ran the model using these parameters and, after reviewing the implied values of future variables (prices, production, acreage), we made some relatively small changes to the matrix of flexibilities of demand from Fuller and Alston (2012). We assume the slope and intercept parameters in the linear demand equations are constant throughout the fifty-year time period. Effects of growth in income and population and other factors are represented by demand growth rate parameters, b^i. Parameter values used in the demand model are shown in table B1.

New and Replacement Plantings

Equations (8a) and (8b) represent the average and marginal cost of investment for new plantings as quadratic functions. The equations were calibrated using region-specific assumptions about the flexibility of the average cost of new plantings, AC, with respect to the quantity of new plantings ($\phi_{AC} = d\ln AC/d\ln PL$):

$$\text{(B2a)} \qquad \mathrm{c}_1 = AC_0\left(1 - \frac{\phi_{AC}}{2}\right),$$

$$\text{(B2b)} \qquad \mathrm{c}_2 = \frac{\partial AC}{\partial PL}\frac{1}{2PL_0} = \phi_{AC}\frac{AC_0}{2PL_0^2},$$

where AC_0 is the initial average cost and PL_0 is the initial value for new plantings. After running the model using a range of values for ϕ_{AC} and discussing the results with experts, we settled on values of $\phi_{AC} = 2/3$ for the southern San Joaquin region, 1/4 for the Napa-Sonoma region, and 1/2 for all other regions. Values for AC_0 can be found in table A3.

The average cost per acre for replacement vines, like the average cost per acre for new plantings, is assumed to be a quadratic function of the rate of replacements but with different parameters, reflecting the fact that it is more costly to replace a single isolated vine than to plant an entire vineyard *de novo*. The parameters c_3 and c_4 were calculated analogously to c_1 and c_2 using estimates from UCCE cost studies:

$$\text{(B3)} \qquad RC_t = \mathrm{c}_3 + \mathrm{c}_4 RP_t^2,$$

where RP represents replantings as an equivalent number of acres. In our estimate of the establishment cost for replacing vines lost to disease, we account for additional labor costs of removing, planting, and maintaining the new vine, which account for the greatest difference between establishment costs of a vine planted after its full life (AC_0) and the cost of a vine replaced prior to

Table B1. Demand-Side Baseline Model Parameters

	Region (j)	Winegrape Quality Region (i) Low	Medium	High
$\overline{p}^i$		279	749	2,615
$\overline{q}^i$		1,715,645	1,388,979	323,531
b^i		0.3	0.3	0.3
h_0^i		336	898	3,277
f_j^i	Low	−0.1668744	−0.0056414	−0.0023680
	Medium	−0.0056414	−0.1671356	−0.0084273
	High	−0.0023680	−0.0084273	−0.2504510
m_j^i	Low	−0.0000271	−0.0000009	−0.0000004
	Medium	−0.0000030	−0.0000902	−0.0000045
	High	−0.0000191	−0.0000681	−0.0020243

Notes: i represents the column and j refers to the row.

Table B2. Yield for Vines *b* Years of Age as a Fraction of Mature Yield (AY_b)

Age of Vines (b)	Region: Southern SJV	Napa-Sonoma	Coastal	Northern SJV	Northern California	Southern California
0	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.50	0.26	0.16	0.55	0.23	0.13
4	0.83	0.66	0.31	1.00	0.42	0.26
5	1.00	1.00	0.64	1.00	0.69	0.61
6–25	1.00	1.00	1.00	1.00	1.00	1.00

Notes: “SJV” refers to the San Joaquin Valley.

Table B3. Variable Cost per Acre as a Function of Age of Acre ($v_{0,b}^i$)

No. of Years since Original Planting (b)	Region: Southern SJV	Napa-Sonoma	Coastal	Northern SJV	Northern California	Southern California
0	0	0	0	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	1,204	2,736	2,155	1,884	2,112	1,204
4	1,246	4,169	2,301	2,100	2,339	1,246
5	1,266	4,333	2,584	2,100	2,339	1,266
6–25	1,266	4,333	2,670	2,100	2,339	1,266

Notes: “SJV” refers to the San Joaquin Valley.

Table B4. Implied Own-Price Elasticities of Supply

Years for Adjustment to Price Change	High Price	Medium Price				Low Price
	Napa-Sonoma	Coastal	Northern SJV	Northern California	Southern California	Southern SJV
5	0.128	0.095	0.099	0.213	0.042	0.120
15	1.237	1.195	0.551	2.233	0.565	0.814
30	2.796	2.499	0.795	4.702	1.132	1.153

Notes: Elasticities represent responses to a permanent, exogenous, 1% increase in the relevant winegrape price, holding all other winegrape prices constant. "SJV" refers to the San Joaquin Valley.

retirement of the acre (RAC_0). To calculate c_3 and c_4, we substitute RAC_0 for AC_0 in equation (B2). RAC_0 was calculated using University of California cost and return studies and information received from consulting with industry experts. These values are reported in table A3.

Variable Costs

Equation (10) represents variable costs. The region-specific parameter, $v^i_{0,b}$, measures variable costs per acre of grapes independent of the total number of acres produced but dependent on the age of a given productive acre. Values for these parameters were estimated based on regional University of California cost and return studies. Values for $v^i_{0,b}$ are given in table B3.

Region-specific land rents, R^i_{t+n}, were calculated using equation (B4), where the intercept and slope are calibrated to regional equilibrium land rent values using ranges from the *2012 Trends in Agricultural Land and Lease* (CCASFMRA, 2012) and expert opinion on the elasticity of land supply. We assumed a virtually infinitely elastic supply of land in all but two regions: Napa-Sonoma and southern San Joaquin Valley. These regions are assumed to have an elasticity of land supply to the winegrape industry of 0.5; the associated coefficients on R^i_1 are given in table A3.

(B4) $$R^i_{t+n} = R^i_0 + R^i_1 A^i_{t+n}.$$

The PD mitigation cost, v^i_1 in equation (10), was taken from interviews with growers, who stated that they spent on average \$150/acre in Napa-Sonoma and Southern California. Elsewhere, $v^i_1 = 0$.