Identifying Economic Hurdles to Early Adoption of Preventative Practices: The Case of Trunk Diseases in California Winegrape Vineyards[1]

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Abstract

Despite the high likelihood of infection and substantial yield losses from trunk diseases, many California practitioners wait to adopt field-tested, preventative practices (delayed pruning, double pruning, and application of pruning-wound protectants) until after disease symptoms appear in the vineyard at around 10 years old. We evaluate net benefits from adoption of these practices before symptoms appear in young Cabernet Sauvignon vineyards and after they become apparent in mature vineyards to identify economic hurdles to early adoption. We simulate production in five regions of California and find widespread benefits from early adoption, increasing vineyard profitable lifespans, in some cases, by more than 50%. However, hurdles to adopt may result from uncertainty about the cost and returns from adoption, labor constraints, long time lags in benefits from early adoption, growers' perceived probabilities of infection, and their discount rate. The development of extension resources to communicate these benefits and potential hurdles to growers are likely to reduce uncertainty, leading to increased early adoption.

Keywords: Grapevine trunk diseases; Early adoption; Plant-disease management; Preventative practices

1. Introduction

Vineyards suffer from damaging wood diseases, which present serious challenges to grape production in every grape-growing region of the world (Bertsch et al., 2013). These diseases, collectively referred to as "trunk diseases" include, among others, Botryosphaeria dieback, Esca and Petri diseases, Eutypa dieback, and Phomopsis dieback. In California, which accounts for approximately 90% of US winegrape production (USDA, 2015), yield losses in susceptible cultivars can reach over 80% in mature vines, during what should be the peak years of production (Munkvold et al., 1994). Siebert (2001) estimated that California winegrape production would generate 14% greater annual gross producer value in the absence of Eutypa dieback.

For all of these diseases, the causal agents are fungi that establish chronic infections of the wood, for which there are no eradicative measures short of cutting off an infected vine and retraining it from the ground up (Sosnowski et al., 2011). Infection occurs primarily through pruning wounds, which are made every dormant season when vines are pruned, starting in year 3 as part of the normal production practices in the vineyard. To minimize such pruning-wound infections by the fungal spores, preventative practices have been developed and are used by practitioners: (*i*) delaying pruning until late in the dormant season, when the risk of infection is low (Petzoldt et al., 1981), (*ii*) double pruning, a modified version of delayed pruning using a mechanical pruning machine to nonselectively trim canes to a uniform height during a first pass in early winter, followed with a second hand-pruning pass in late winter to remove wood infected after the first pass and adjust to traditional 2-bud spurs (Weber et al., 2007), and (*iii*) applying fungicides to fresh pruning wounds as a protective barrier (Amponsah et al., 2012; Halleen et al., 2010; Pitt et al., 2012; Rolshausen and Gubler, 2005; Rolshausen et al., 2010; Sosnowski et al., 2008; Sosnowski et al., 2013). As these practices are preventative in nature, they must be used before vines are infected to ensure optimal efficacy.

Pest-control advisers (PCAs) working in grape production systems acknowledge the widespread nature of trunk diseases in California vineyards and their impact on yields (Hillis et al., In press). Nonetheless, PCAs have a greater tendency to recommend preventative practices in vineyards where vines with symptoms are widespread, which is typically when the vineyard is 10 or more years-old (Duthie et al., 1991). However, by definition, the benefits of prevention are minimal when the vines are already infected. This habit of recommending preventative practices in mature, diseased vineyards can be explained in part by the fact that trunk diseases are not typically apparent until years 8-10; infections occur when the vineyard is young, but symptoms take several years to appear. By year 10, approximately 20% of vines present symptoms (Duthie et al., 1991) and up to this point, yield losses are relatively minor (Munkvold et al., 1994).

Recommendation of preventative practices in diseased vineyards by PCAs may also be explained by a gap in the research. Although preventative practices have been tested by researchers in many short-term experimental trials (Rolshausen et al., 2010; Urbez-Torres and Gubler, 2011; van Niekerk et al., 2011; Weber et al., 2007), their long-term efficacy has been the subject of far fewer studies (Gu et al., 2005). Practitioners may thus be hesitant to adopt preventative practices in younger vineyards because improvements to yields and net returns have not been quantified. The benefits (fewer yield losses) are also uncertain and difficult to measure in the future, with practice costs being immediate in the short-term.

Our work addresses the economic factors that may result in a delay to adopt preventative practices in young vineyards by providing a more transparent description of the costs and benefits. We simulate winegrape production for representative vineyards in five of California's diverse grape growing regions. The regions are located within California Grape Pricing Districts or 'Crush districts' as follows: Napa (Crush District 4), northern San Joaquin (Crush District 11), Central Coast (Crush District 8), Lake (Crush District 2), and Sonoma (Crush District 3). Our parameters include disease-control efficacies from published experimental trials and vineyard practice costs from economic budgets for producing Cabernet Sauvignon, one of the most widely-planted winegrape cultivars in California. Cabernet Sauvignon is not known to be the most susceptible cultivar to any of the trunk diseases (Travadon et al., 2013), but we use it as an example of winegrape production because it has similarly large production acreage in all five regions. Also, it is the cultivar most widely considered in the published Cost & Return studies (UCCE, 2004-2014), which form the basis for the economics analysis. We derive annual net returns for a healthy vineyard, an infected vineyard in which no management practices are used (infected-untreated), and an infected vineyard in which preventative practices are adopted in years 3, 5, or 10. These ages were selected to evaluate conditions when vines are fully trained onto the trellis system and winter pruning begins (3 years old), when vines reach maturity (5 years old), and when trunk disease symptoms typically appear in vineyards (10 years old). In this way, we quantify the cumulative yield and revenue losses due to inaction, and the levels to which they are mitigated by prevention.

2. Background

The research described in this paper adds to the literature on adoption of disease-prevention practices. Past research on adoption of agricultural technology and innovation has primarily analyzed annual crops (Alston et al., 2010). More recent work on perennial crops, wine grapes in particular, has considered managing Pierce's disease (Alston et al., 2013, 2014; Tumber et al., 2014), powdery mildew (Fuller et al., 2014; Lybbert and Gubler, 2008), and grapevine leafroll disease (Atallah et al., 2014; Fuller et al., 2015; Fuller et al., 2014; Lybbert and Gubler, 2008; Ricketts et al., 2015). Siebert (2001) provided insight into the economic impact of Eutypa dieback to California's wine grape industry. Sipiora and Cuellar (2014) examined farm-level impacts of preventative practices against Eutypa dieback in a Napa vineyard on annual yields and net present value. Our economic analysis contributes to this literature by providing the first study, to our knowledge, to evaluate economic hurdles to adopting preventative practices in young versus mature vineyards.

2.1. Economic simulation model

We develop simulation scenarios that consider future management costs and benefits (i.e., amelioration of cumulative yield losses by adopting preventative practices) based on past observations (i.e., increasing disease incidence and the associated yield losses over time), similar to other recent research on grapevine diseases (Alston et al., 2013, 2014; Fuller et al., 2015; Fuller et al., 2014), given that field experiments would take decades to complete. Like these past studies, we use information on currently available practices, their costs, and effects on yields and lifespan to establish baseline conditions and scenarios from University of California Cooperative Extension Cost and Return Studies, historical data from the California Department of Food and Agriculture (CDFA) and the United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), the scientific literature, and interviews with winegrape growers, farm advisors, and other stakeholders to capture the dynamics of trunk disease infections and net returns in the different winegrape districts. Our approach to modeling the economics of trunk diseases requires a different framework, however, given that trunk diseases may not have measurable impacts on yield until many years after infection. Our model captures time-varying yield and practice costs through adopting preventative practices (Table 1) at different vineyard ages, relative to taking no action (i.e., in an infected-untreated vineyard). We examine changes in returns and costs to the grower over a 25-year period holding all other factors constant, except practice costs and yield losses. In this way, this model allows us to compare long-run average outcomes without incorporating unknown and unpredictable future events, and alleviate the inherent challenges in modeling current and future expectations.

{Insert Table 1 here}

An important factor in studying winegrapes in California is the regional variation in yield and price per ton.[2] Our modeling approach accommodates such heterogeneity. For example, at one extreme in the Napa and Sonoma regions (Crush Districts 4 and 3 respectively), establishment decisions and management practices restrict vineyard yields (approximately 4.5 to 5 tons of Cabernet Sauvignon per acre in mature vineyards) with the goal of achieving higher wine quality that sells at a high average price ($2,355 and $5,192 for Sonoma and Napa, respectively). At the other extreme, in the northern San Joaquin Valley (Crush district 11), fruit prices are much lower ($650 per ton) and vineyards produce higher yields (10 tons per acre (CDFA/NASS, 2015). The other regions face prices and yields within these two extremes.

2.2. Disease-Control Efficacy of Preventative Practices

Our survey of the scientific literature on preventative practices provided a range of disease-control efficacies (DCEs), which were calculated from multiple experimental trials on different trunk diseases (Table 2). DCE is the proportion of pruning wounds which do not become infected as a result of a preventative practice. In the empirical analysis, we use DCEs of 25, 50, and 75%, which reflect the range of natural variation across study years [e.g., DCEs

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[2] The Appendix contains the yield and price information for each of the regions considered in the analysis.

ranging from 29 to 88% for delayed pruning against *Phaeoacremonium minimum* (Larignon and Dubos, 2000)] or across pathogens [e.g., DCE of 52% for Topsin against *Phaeomoniella chlamydospora* vs. DCE of 80% against *Lasiodiplodia sp.* (Rolshausen et al., 2010)]. The high extreme of our range in DCEs is truncated at 75% to reflect that all infections may not arise through pruning wounds. For example, planting material may be infected in the nursery (Gramaje and Armengol, 2011) and, thus, it is unrealistic to assume a practice can prevent 100% of infections.

{Insert Table 2 here}

The experimental trials on preventative practices are fragmented. They were conducted by different labs, on different cultivars, in different regions, and in different years. All trials involved controlled inoculations, which ensured that the pruning wounds were 'challenged' by individual species of trunk pathogens and, thus, the practice efficacy in preventing infection was tested. Nonetheless, trunk diseases occur in mixed infections in the vineyard, where individual vines are often infected by multiple trunk pathogens, which attack vines through different pruning wounds in different years. Cultivar susceptibility is not consistent across trunk pathogens, based on the few studies that have been done [e.g., (Travadon et al., 2013)].

3. Methods: Bioeconomic model

We develop a representative farm mathematical program to simulate the dynamic economic decision making involved when investing in perennial crops, such as winegrapes. The perennial nature of the crop, its relatively long life-expectancy (on the order of decades), and the multi-year delay between infection and symptom expression suggest a dynamic model is more appropriate than a static model. A dynamic model allows us to capture the effects of decisions made today and in the future on investments in preventative practices in vineyards. Although, productivity is theoretically stable after a vineyard matures, symptoms of trunk diseases are not apparent until vines mature, and they worsen over time because the infections are chronic. With a dynamic model, we can capture the effects of these diseases on time-varying yield per acre and of currently available preventative practices adopted at different vineyard ages. We are then able to compare these practice scenarios with a ‘no action’ scenario, and measure the changes in costs and returns not just today, but in the future as well.

3.1. Biological model

The population dynamics of trunk disease incidence in a California winegrape vineyard follow a logistic growth function characterized in Duthie et al. (1991). Munkvold et al. (1994), using test plots of Chenin blanc and Barbera varietals throughout Merced County, California, estimated yield loss from Eutypa Dieback. We apply this relationship to Cabernet Sauvignon in the other districts across all trunk diseases, following discussions with growers, managers, and farm advisors on their experiences with trunk diseases. Mathematically, disease incidence grows over time according to

$$Y_t = \frac{A}{(1+B_0 e^{-C_0 t})} = \frac{0.92}{(1+919e^{-0.55t})} \tag{1}$$

where Y_t is the percentage of symptomatic vines per acre, A is the carrying capacity, t is the age of the vineyard, B_0 is the constant of integration $(A\text{-}Y_0)/Y_0$, Y_0 is the initial percentage of symptomatic vines and equals 0.001, and C_0 is the growth rate. Figure 1 shows this growth over the 25-year lifespan evaluated in the empirical analysis.[3]

{Insert Figure 1 here}

Growth is negligible over the early years with a little over 1.5% of vines presenting symptoms by the time a vineyard is 5 years old. The rate accelerates rapidly shortly thereafter with 7.5% of the vines having symptoms by year 8, nearly 20% by year 10, and 75% by year 15. This is a worst-case scenario, in a vineyard where disease incidence increases rapidly due to a variety of factors (e.g., high susceptibility of the grape cultivar, optimal climate conditions for infection, absence of management practices against trunk diseases), the impacts of which have not been quantified. This increase in disease incidence translates into yield reductions based on Munkvold et al. (1994) as follows

$$Yield_t^I = (100.1 - 98.81Y_t) * Yield_t^H \tag{2}$$

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[3] This lifespan is consistent with California winegrape production as reported in the UCCE Cost and Return Studies.

where $Yield_t^H$ and $Yield_t^I$ are annual tons per acre produced by a healthy and an infected-untreated vineyard, respectively. This function takes into account that vines may compensate for lost fruiting positions, toxins from trunk pathogens may affect apparently healthy shoots, and in more severe cases, symptomatic vines may produce less photosynthate, thereby negatively affecting yield. When preventative practices are adopted, there are fewer symptomatic vines over time, lowering the reduction of yields throughout the 25-year lifespan of a vineyard. Figure 2 illustrates reduction in yields as disease incidence increases for one of the winegrape regions.[4] How preventative practices affect this relationship is discussed below. Yield per acre values for the different regions used in the empirical analysis are contained in Table A.1 in the Appendix.

{Insert Figure 2 here}

3. 2. Economic model

When deciding whether to adopt one practice over another or a practice versus no action, a grower may weigh the cumulative expected present value of annual net returns over a 25-year vineyard lifespan across the possibilities based on their perceived risk of infection. Annual net returns per acre (NR) are defined as

$$NR_t(A, c, dce) = Price_t \text{ x } Yield_t(A, dce) - Cost_t(A, c) \tag{3}$$

where *A* denotes the age when adoption occurs, *c* the practice cost, *dce* the DCE, and *t* the age of the vineyard. Figure 3 shows the stream of net returns in 2013 dollars over a 25-year vineyard

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[4] Figures showing the effect of trunk diseases in other regions are available on request.

lifespan for the northern San Joaquin region. A grower with a healthy vineyard versus one with an infected-untreated vineyard can expect to make \$55,496 per acre and -\$21,669, respectively, over this time. A grower is likely to replace or abandon the vineyard before the 25th year is reached if annual returns are negative. However, we extend production out to 25 years so we can compare across similar lifespans.

{Insert Figure 3 here}

The cumulative discounted stream of net returns (*PVNR*) or simply net benefits (*NB*) across the scenarios are

$$NB(A, c, dce, \delta) = \sum_{t=0}^{25} \frac{NR_t(\cdot)}{(1+\delta)^t} \tag{4}$$

Table 3 shows NB per acre when the real discount rate (δ) is assumed to be 3%, for a healthy vineyard and an infected-untreated vineyard, across the five districts examined. Clearly taking no action to prevent trunk diseases results in significant economic losses. The greatest potential losses are in Napa, reaching over \$160,000 per acre. Presumably, some growers are likely to replant an infected vineyard or use vine surgery [(physically cutting out infected wood and retraining a new cordon or a new vine from the trunk (Sosnowski et al., 2011)] to treat symptomatic vines (and thus restore yields) before the 25 years have passed, making \$160,000 per acre an upper bound on potential losses over 25 years.

{Insert Table 3 here}

The expected net benefits ($E[NB]$) for each scenario are then

$$E[NB(A,c,dce,\delta)] = (1-\pi)NB^{H}(A,c,dce,\delta) + \pi NB^{I}(A,c,dce,\delta) \qquad (5)$$

where the superscripts denote healthy or infected vineyards, respectively, and π is the grower's perceived probability of infection. Figure 4 shows $E[NB(\cdot)]$ for no action (NA) and for adoption of a known preventative practice when the vineyard reaches A_0 years old, for different perceived probabilities of infection (π). This model can provide both prescriptive and predictive information. With this model we can see how a grower will respond to changes in model parameters (A, c, dce, δ) given their knowledge of costs and returns, and perception of disease infection. This model can also provide a reference guide that shows, given a grower's knowledge of their costs and benefits, whether it is better to adopt early or to wait until symptoms appear.

In this framework, a grower maximizes his or her wellbeing by selecting the scenario with the greatest $E[NB(\cdot)]$. The intersection of these lines, at π^0, divides the population of growers with varying perceptions of the probability of infection. In general, if a grower who knows the cost and benefits from adopting these preventative practices, has a perceived probability of infection less than π^0, they would be expected to not adopt a practice, those with a perceived probability of infection greater than π^0 would, and those at π^0 would be indifferent to adopting. When symptomatic vines appear in the vineyard, perception gives way to observation, the probability becomes one and we would expect growers adopt the practice. This would be consistent with the findings of Hillis et al. (In press) at least for PCAs, who tended to recommend preventative practices more often in vineyards with a greater percentage of symptomatic vines. Over time, grower perceptions of the probability of infection will likely increase as a result of experiential or scientific evidence and thus a greater share of growers would be expected to adopt in the future.

{Insert Figure 4 here}

We derive a general expression for the perceived probability π^0 that divides adopters and nonadopters by equating the expected net benefits from no action

$$ENB(NA,\delta) = (1-\pi)NB^H(NA,\delta) + \pi NB^I(NA,\delta), \tag{6}$$

with the expected net benefits from adopting a practice

$$E[NB(A,c,dce,\delta)] = (1-\pi)[NB^H(A,c,dce,\delta)] + \pi[NB^I(A,c,dce,\delta)] \tag{7}$$

and given the assumption that adoption of a preventative practice does not affect yields in a healthy vineyard we rewrite equation 7 as

$$E[NB(A,c,dce,\delta)] = (1-\pi)[NB^H(NA,\delta) - C(A,c,\delta)] + \pi[NB^I(A,c,dce,\delta)] \tag{8}$$

where $C(A,c,\delta)$ are the cumulative discounted practice costs over the years of adoption, which increases with decreases in A and δ, and increases in c, while $NB(\cdot)$ increases with increases in *dce* and decreases in A, c, and δ. Solving for π^0 produces the general expression

$$\pi^0(A, c, dce, \delta) = \frac{C(A,c,\delta)}{NB^I(A,c,dce,\delta) - NB^I(NA,\delta) + C(A,c,\delta)} \tag{9}$$

The equilibrium switching point (π^0) defined in equation 9 changes with changes in the age of the vineyard at the point when adoption occurs (A), practice cost (c), disease control efficacy (*dce*), or the discount rate (δ). Evaluating the comparative statics with respect to these factors shows: 1) when vineyard age at time of adoption changes, the change in the proportion of adopters is ambiguous, suggesting that some who adopt may wait to do so; 2) when practice costs increase, the probability of infection increases, reducing adoption; 3) when *dce* increases, the probability of infection falls, increasing adoption; and 4) when δ changes, the change in the proportion of adopters is ambiguous.

To see this, we first take the derivative of the equilibrium condition with respect to A, yielding[5]

$$\frac{\partial \pi(A)}{\partial A} = \frac{\frac{\partial C(A)}{\partial A}\left[NB^I(A_0) - NB^I(NA) + C(A)\right] - C(A)\left[\frac{\partial NB^I(A)}{\partial A} + \frac{\partial C(A)}{\partial A}\right]}{\left[NB^I(A_0) - NB^I(NA) + C(A)\right]^2} \tag{10}$$

The two products in the numerator are both positive, while the term in the denominator is positive. As such, to infer the conditions for the direction of this change, we set the numerator less than zero and solve

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[5] Some subscripts are removed to simplify presentation.

$$\frac{\partial C(A)}{\partial A}\left[NB^{I}(A_0) - NB^{I}(NA) + C(A)\right] - C(A)\left[\frac{\partial NB^{I}(A)}{\partial A} + \frac{\partial C(A)}{\partial A}\right] < 0 \tag{11}$$

Rearranging terms yields,

$$\frac{\frac{\partial C(A)}{\partial A}}{C(A)} < \frac{\left[\frac{\partial NB^{I}(A_0)}{\partial \delta}\right]}{[NB^{I}(A_0) - NB^{I}(NA)]} \tag{12}$$

or, as shown graphically in Figure 5,

$$\frac{\Delta C}{C(A)} < \frac{\Delta NB_A}{NB_{A_0}} \tag{13}$$

When the percentage increase in the cost of the practice (given it is adopted sooner rather than later) is less than (greater than) the percentage increase in the net benefits from adopting earlier, then the probability will fall (rise). This shows theoretically that a grower acting in their best interest may delay adoption. That is, a practice that has greater overall economic benefits in an infected vineyard when adopted early may not be adopted early by some growers because the expected relative gains in an infected vineyard from adoption are not enough to compensate them for the expected relative cost they face if the vineyard is healthy.

{Insert Figure 5 here}

Not surprisingly, when we evaluate a change in the practice cost,

$$\frac{\partial \pi(A)}{\partial c} = \frac{\frac{\partial C(A,c,\delta)}{\partial c}\left[NB^{I}(A,c,dce) - NB^{I}(NA,c) + C(A,c)\right] - C(A,c)\left[\frac{\partial NB^{I}(A,c,dce)}{\partial c} + \frac{\partial C(A,c)}{\partial c}\right]}{[NB^{I}(A,c,dce) - NB^{I}(NA) + C(A,c)]^{2}} \qquad (14)$$

$$\frac{\partial \pi(A)}{\partial c} = \frac{\frac{\partial C(A,c)}{\partial c}\left[NB^{I}(A,c,dce) - NB^{I}(NA,c)\right] - C(A,c)[\frac{\partial NB^{I}(A,c,dce)}{\partial c}]}{[NB^{I}(A,c,dce) - NB^{I}(NA) + C(A,c)]^{2}} > 0 \qquad (15)$$

we see the potential share of growers who adopt also falls as the switching point moves outward from zero, given the first term in the numerator of equation 15 is positive because the change in the overall cost increases with a change in the practice cost and taking action results in greater net benefits, and the second term in the numerator is negative because an increase in the practice cost decreases the net benefits from adoption in an infected vineyard. .

If DCE were to change, then

$$\frac{\partial \pi(A)}{\partial dce} = \frac{-C(A,c)[\frac{\partial NB^{I}(A,c,dce)}{\partial dce}]}{[NB^{I}(A,c,dce) - NB^{I}(NA) + C(A,c)]^{2}} < 0 \qquad (16)$$

That is, π^0 moves in an opposite direction to changes in *dce* because the numerator is negative given that increases in DCE increase yield per acre and thus increase net benefits.

Lastly, we consider a change δ, as growers are not all likely to have the same intertemporal preferences. The comparative static with respect to δ is

$$\frac{\partial \pi(\cdot)}{\partial \delta} = \frac{\frac{\partial C(\cdot)}{\partial \delta}\left[NB^{I}(A_0) - NB^{I}(NA) + C(\cdot)\right] - C(\cdot)[\frac{\partial NB^{I}(A_0)}{\partial \delta} - \frac{\partial NB^{I}(NA)}{\partial \delta} + \frac{\partial C(\cdot)}{\partial \delta}]}{[NB^{I}(A_0) - NB^{I}(NA) + C(A)]^{2}} \qquad (17)$$

and given the decrease in $\frac{\partial NB^I(A_0)}{\partial\delta}$ is greater than the decrease in $\frac{\partial NB^I(NA)}{\partial\delta}$, the two products in the numerator are both negative. To determine the sign we set the numerator less than zero and solve

$$\frac{\partial C(\cdot)}{\partial\delta}[NB^I(A_0) - NB^I(NA) + C(\cdot)] - C(\cdot)[\frac{\partial NB^I(A_0)}{\partial\delta} - \frac{\partial NB^I(NA)}{\partial\delta} + \frac{\partial C(\cdot)}{\partial\delta}] < 0 \qquad (18)$$

Rearranging terms yields,

$$\frac{\frac{\partial C(\cdot)}{\partial\delta}}{C(\cdot)} < \frac{\left[\frac{\partial NB^I(A_0)}{\partial\delta} - \frac{\partial NB^I(NA)}{\partial\delta}\right]}{[NB^I(A_0) - NB^I(NA)]} \qquad (19)$$

When the percentage decrease in the cost of the practice is less than (greater than) the percentage decrease in the net benefits, then the probability will fall (rise) with a change in the discount rate. The long term nature of the diseases' effect of yields means the benefits from adoption are not realized until later in a vineyard's lifespan. Further, the costs are uniformly distributed throughout that lifespan. If these future benefits from adoption are large (i.e., the practice is highly effective) and exceed the reduction in costs, then we would expect that an increase in the discount rate increases π^0, and vice versa.

Without knowing the distribution for grower perceptions of probability of infection, or how it might change over time, we cannot determine the number of growers who will adopt now or in the future. We assume the dividing probability defined in equation 9 is relatively close to 1, based on the findings of Hillis et al. (In press), since PCAs report many vineyards have trunk disease. We also see, in the empirical analysis to follow, that π^0 is in some cases very close to zero, which suggests that many growers should be adopting early. Unfortunately this is not the case, as few PCAs recommend preventative practices in vineyards with low disease incidence and large majorities of growers are not adopting preventative practices in young vineyards (Hillis et al., In press).

3. 3. Simulated economic experiment

In the simulated economic experiment, annual costs and benefits from winegrape production over a 25-year lifespan are estimated using budgets taken from the University of California Cooperative Extension (UCCE) Cost and Returns Studies (UCCE, 2004-2014) and historical price data gathered from California grape crush reports published annually by USDA-NASS. Appendix A contains the parameter values used in the analysis. Dollar values are in 2013 dollars to control for inflation and are discounted using a 3% real discount rate to reflect growers' intertemporal preferences. As noted previously, this budget approach has been used in Alston et al. (2013), Alston et al. (2014), Fuller et al. (2014), and Fuller et al. (2015). Each scenario has the same cultural practices, but differs by winter pruning practice and the additional cost associated with the practice (see Table 4). This condition allows us to conduct a simulated economic experiment using pairwise comparisons of alternative scenarios reflecting different ages of adoption, practice costs, and DCEs, to determine the role that net benefits, costs, DCE, and grower perception play in grower reluctance to adopt these practices early in the life of the vineyard.

{Insert Table 4 here}

The baseline model for each district simulates production from a healthy vineyard and then subjects it to a trunk disease, assuming no preventative action is taken. We then simulate scenarios across the three practices with different additional cost per acre over and above the cost of standard winter pruning at different ages (3 years old, 5 years old, and 10 years old) with varying DCEs (25%, 50%, and 75%).

As noted above, DCE measures the percentage of asymptomatic vines (assumed to not be infected) that would otherwise be symptomatic (assumed to be infected) if the practice had not been adopted. The bioeconomic model is altered to reflect the change in disease incidence by reducing the increasing percentage of symptomatic vines and restarting the time to reflect the new path as follows

$$Y_t = \begin{cases} \frac{A}{(1+B_0 e^{-C_0(t)})} & \text{if } t < age \\ \frac{A}{\left(1+B_{age} e^{-(dce * C_0(t-age)}\right)} & \text{if } t \geq age \end{cases} \tag{20}$$

where $B_{age} = (A - Y\text{age})/Y\text{age}$ and $Y\text{age}$ is the percentage of symptomatic vines at the time adoption begins.[6]

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[6] For the simulation model B_{age} equals 305.9085, 58.7497, and 7.469187 for adoption in year 3, 5, and 10, respectively, given the logistic growth model specified in equation 1.

4. Results and discussion

The effects of these preventative practices on yield, when adopted at different ages, are shown in Figure 6 for a representative northern San Joaquin vineyard. We see practices adopted sooner and with greater DCE (in an infected vineyard) generate yields that increasingly approach those of a healthy vineyard; net returns follow accordingly.

{Insert Figure 6 here}

Figure 7 shows the effect of adopting different practices at different ages, assuming a 75% DCE. The sooner the practice is adopted, the greater the net benefits. Figure 8 shows the effect of DCE for double pruning, the most costly practice. When DCE is low, the net benefits of adopting double pruning may not be enough to generate positive overall returns. Table 5 contains the cumulative discounted net benefits for each scenario relative to taking no action. In all scenarios, the greatest net benefits occur when a practice is adopted in year 3. The bolded values in Table 5 reflect positive cumulative net benefits for the corresponding scenario. Most practices adopted in year 10 are not sufficient to produce positive net benefits over the 25-year lifespan. Early adoption gives a grower the best chance to earn positive net benefits. These results assume growers continue to operate their vineyards the entire 25 years. It is possible they will retrain or replant a vineyard before the 25 year period ends. This is why we next evaluate the profitable lifespan across scenarios.

{Insert Figure 7 here}

{Insert Figure 8 here}

{Insert Table 5 here}

A 25-year lifespan is the assumed productive life of a vineyard in California, which is in line with past economics studies (Alston et al., 2013, 2014; Fuller et al., 2015; Fuller et al., 2014; Tumber et al., 2014), evidence from the field, and from discussions with growers, advisors, and others involved in winegrape production. Untreated trunk disease infections may drastically reduce the number of years that a vineyard generates positive returns. As noted in Table 6, the overall lifespan of infected-untreated vineyards are likely to be cut by roughly 50%.

{Insert Table 6 here}

When preventative practices are adopted, we see that early adoption and greater DCE can increase the number of years a grower can expect positive net returns (Table 7). More specifically, the data suggest that adoption at the earliest vineyard age we consider (3 years old) with the lowest efficacy rate (25% DCE) can provide up to three to four years of additional positive net returns. Adoption of a practice with a DCE of 50% produces positive net returns for 18 to 25 years. A practice with 75% DCE will produce positive net returns for the full 25 years, except when adopted in year 10 (i.e., after symptomatic vines are present).

{Insert Table 7 here}

Our findings suggest that growers have economic incentives to adopt preventative practices, and to do so in young vineyards, especially for delayed pruning, which pays for itself immediately because there is no direct cost associated with adoption.[7] Growers may be reluctant, however, to adopt the other practices because of the length of time it takes for them to outperform taking no action. The time it takes for a practice to outperform no action is heavily influenced by disease incidence. When the vineyard is young, there are few to no symptomatic vines. The benefits from early adoption are thus not realized early, but rather much later when disease incidence increases rapidly. Looking at the cumulative discounted net benefits in Table 8, we see that even when Topsin is assumed highly effective (75% DCE) and adopted in year 3, it can take up to 4 to 5 years to outperform no action. When the more expensive double pruning is adopted in year 3, it may take upwards of 7 to 8 years to outperform no action. We also see adoption in year 5 outperforms no action at roughly the same age as adopting in year 3. When double pruning is adopted and it has 75% DCE, we see the first indication that growers may have an incentive to adopt later. In two of the five districts, the age when a practice outperforms no action is sooner when adopted in year 5 than when adopted in year 3. Furthermore, adopting practices in year 10 outperforms no action immediately (or within a few years) in all cases. A grower who is uncertain about the probability of infection or about DCE, and is not thinking about maintaining a vineyard for 25 years, may thus be reluctant to adopt.

{Insert Table 8 here}

As noted earlier, the time it takes for a practice to outperform is not the only possible reason growers may be reluctant to adopt early. The perceived probability of infection may also

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[7] Although there are no direct additional costs to delayed pruning, it is not possible to delay pruning in all vineyards given labor constraints; attempting to delay pruning in all vineyards could increase demand for labor and thus raise labor costs.

influence the decision to adopt early. Table 9 shows the cumulative discounted net benefits for a healthy vineyard when adoption occurs at different ages. Delayed pruning is not considered here as it does not add cost and thus the cumulative net benefits from a healthy vineyard are identical to those when delayed pruning is adopted. The net benefits of Topsin application and double pruning are needed to derive the perceived probabilities of infection (π^0), in equation 9 above and displayed in Table 10. We see in Table 11, that higher discount rates typically result in higher π^0 and a lower proportion of adopters, except when double pruning is adopted in year 10, assuming DCE rates of 25% and 50% (as noted by the bolded values). The decrease in these benefits are too small to offset the decrease in costs given the higher discount rate, resulting in a greater proportion of adopters.

{Insert Table 9 here}

{Insert Table 10 here}

{Insert Table 11 here}

The difference in the cost of the practices heavily influences the probabilities. Topsin, which is less costly than double pruning, has noticeably lower probabilities than double pruning, suggesting a higher rate of adoption. When grower perception of DCE is low and cost is high, as is the case for double pruning, the estimated perceived probability (π^0) is close to or equal to 1, implying that the share of growers who do not adopt could be at or close to 100 percent. Further, when grower perception of DCE is high, the expected net benefits from adopting earliest do not always outweigh the additional expected cost of acting. This suggests there is a small window in which some growers may prefer adopting in year 5 rather than year 3.

5. Conclusion

We find in all scenarios, a grower is better off adopting a preventative practice than taking no action in infected vineyards. In addition, our findings suggest a grower who adopts a preventative practice in year 3 will see the greatest net returns possible. These net returns also illustrate the profitable lifespan of an infected vineyard can be reduced a few years to more than 50% when adopting in year 10. These shortened lifespans, even in the face of attempting to prevent disease, may lead growers to question the efficacy of the practices.

From discussions with growers, we believe that the length of time it takes for a practice to outperform, in terms of cumulative net returns, another practice or no action also affects grower perception of practice efficacy. We estimate that it takes from 2 to 10 years, depending on DCE and practice cost, for a preventative practice adopted in year 3 to outperform no action. When a practice is adopted in year 5, it outperforms no action within 8 years, again depending on DCE and practice cost. Practices adopted in year 10 may take up to 4 years to do the same. These results suggest growers likely perceive these preventative practices as less effective than they actually are, especially when adopted at the earliest possible time.

We next estimate the perceived probability of infection that divides growers between adopters and non-adopters by comparing expected cumulative discounted net returns for each scneario with an infected untreated vineyard. We find that when practice costs are low (under $100 per acre) these probabilities are under 10% for all districts. Evidence from a recent survey suggests widespread prevalence of trunk diseases among California vineyards (Hillis et al., In press). If so, growers' perception of probability of infection are closer to one. Our result then implies a large majority of growers should be adopting these practices when their vineyards are 3 years old even in the face of low DCE and low probability of infection. When costs are high, these probabilities approach 1, indicating many will not adopt or will wait until they are certain. We also discovered when a grower is uncertain about the probability of infection, earlier adoption may not be preferred even though adopting earliest in an infected vineyard is optimal.

Grower perception of the DCE of a practice could be swayed by the length of time it takes for preventative practices (across all DCEs) to outperform no action, thereby delaying their decision to adopt. This time lag is heavily influenced by disease incidence, which results in benefits of adoption being realized much later in the vineyard's lifespan. Informing growers of the long-term benefits of early adoption, given the high likelihood their vineyard becomes infected, may alleviate this factor. Other disincentives to adopt early likely relate to incomplete or imperfect information about DCE or the probability of infection. Development of effective extension tools, providing growers with the scientific evidence from field trials, for example, could address these factors. In addition, development of an early detection tool, alerting growers to the presence of trunk-disease pathogens in young vineyards, could eliminate uncertainty about infection. The widespread prevalence of trunk diseases throughout California suggests, if cost effective, early detection could tip the scales toward greater rates of early adoption. Future research quantifying this effect and measuring the economic benefit of early adoption could enhance an extension program designed to increase awareness about trunk diseases and possible early adoption of preventative practices.

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FIGURE CAPTIONS:

Fig. 1. Trunk Disease Incidence (in % symptomatic vines/acre by the age of the vineyard (Duthie et al. 1991). Note: Duthie et al. (1991) measured Eutypa dieback symptoms and dead spur positions, the latter of which is now known as a general symptom of three trunk diseases (Botyrosphaeria dieback, Eutypa dieback, and Phomopsis dieback).

Fig. 2. Effect of Trunk Diseases on Yield by Vineyard Age in a Cabernet Sauvignon Vineyard in the Northern San Joaquin Region. Note: Effect of infection on yield from Munkvold et al. (1994). Yield data come from UCCE (2012).

Fig. 3. Cumulative Undiscounted Net Returns (Total Revenue – Total Cost) per acre for Healthy versus Infected-Untreated Cabernet Sauvignon Vineyards in Northern San Joaquin Region (in 2013 dollars).

Fig. 4. Expected Net Benefits for Infected-Untreated Scenario and Representative Adoption Scenario as a Function of Grower Perception of Disease Risk. The probability π^0 separates growers into adopters with perceived probabilities of infection greater than π^0 and non-adopters with perceived probabilities of infection less than π^0.

Fig. 5. The effect of perceived Probability of Infection Falls when Adopting Earlier (A_1) if the percentage increase in the cost of the practice when the vineyard is healthy ($\Delta C/C(A)$) is less than the percentage increase in Net Benefits when the vineyard is infected ($\Delta NB_A/NB_A$).

Fig. 6. Tons/Acre for Different Ages of Adoption and Disease Control Efficacy for a Northern San Joaquin Cabernet Sauvignon Vineyard.

Fig. 7. Cumulative Net Returns for 75% Disease Control Efficacy Practices adopted at Different Vineyard Ages for Northern San Joaquin Cabernet Sauvignon.

Fig. 8. Cumulative Net Returns for Double Pruning adopted at Different Vineyard Ages for Northern San Joaquin Cabernet Sauvignon.

Table 1. Description of preventative practices for management of grapevine trunk diseases.

Practices	Description
Delayed Pruning	Prune late in the dormant season (February or later, before budbreak) by hand, when both pathogen inoculum and wound susceptibility are lower, hence minimizing the risk of infection compared to December and January.
Double Pruning	Prune early in the dormant season (December or January) with a mechanical-pruning machine; partially prune canes to a length of approx. 0.4 m. Prune again late in the dormant season (February or later) by hand to two-bud spurs, to remove potentially infected canes.
Topsin	Topsin is a fungicide that provides a protective barrier on pruning wounds against infection by the spores of trunk pathogens. After pruning and before rain, the latter of which induces spore production, liberation and dispersal, apply Topsin by hand with a paintbrush or sponge to cover pruning wounds.[8]

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[8] Protectants registered for hand application during the dormant season in California are Thiophanate-methyl (Topsin M WSB; United Phosphorus, Inc., King of Prussia, Pennsylvania), Boric acid (Tech-Gro B-Lock; Nutrient Technologies, Inc., Dinuba, California), and VitiSeal (VitiSeal International LLC, San Diego, California). Topsin is also registered for spray application.

Table 2. Disease control efficacies (DCEs; % pruning wounds protected) for preventative practices against three trunk diseases and six trunk pathogens. For Topsin, values are calculated as a reduction in pathogen recovery from treated-inoculated pruning wounds, relative to that of nontreated-inoculated pruning wounds. For delayed pruning and double pruning, values are calculated as a reduction in pathogen recovery from late-winter pruning wounds, relative to that of early-winter pruning wounds. Ranges reflect data from replicated studies in the same vineyard across two years.

Trunk disease	Preventative practices		
Trunk pathogen	Topsin	Delayed pruning	Double pruning
	DCE (*% pruning wounds protected*)		
Botryosphaeria dieback			
Lasiodiplodia sp.	80%[a]	59 – 75%[c]	-
Neofusicoccum luteum	60%[b]	-	-
Neofusicoccum parvum	-	55 – 79%[c]	-
Esca			
Phaeoacremonium minimum	57%[a]	29 – 88%[d]	-
Phaeomoniella chlamydospora	52%[a]	40 – 58%[d]	-
Eutypa dieback			
Eutypa lata	100%[a]	90%[e]	33 – 85%[f]

[a] When applied to Chardonnay in 2005 and Zinfandel in 2006; averaged across both cultivars/years (Rolshausen et al., 2010).

[b] When applied to Chardonnay (Amponsah et al., 2012).

[c] When pruning Cabernet Sauvignon and Chardonnay in March versus December, in 2007 and 2008 (Urbez-Torres and Gubler, 2011).

[d] When pruning Cabernet Sauvignon in March versus January, in 1997 and 1998 (Larignon and Dubos, 2000).

[e] When pruning Grenache in March versus December (Petzoldt et al., 1981).

[f] When pruning Chardonnay and Merlot in February versus December, in 2001 and 2002 (Weber et al., 2007).

Table 3. Cumulative discounted net benefits (NB) per acre for healthy and infected-untreated vineyards over a 25-year lifespan (in 2013 dollars), by region.

	Healthy vineyard	Infected-untreated vineyard
Region (Crush District number)	*NB per acre*	
Napa (4)	$203,982	$42,271
Northern San Joaquin (11)	$33,019	-$11,957
Central Coast (8)	$59,372	-$6,144
Lake (2)	$40,375	-$4,601
Sonoma (3)	$49,496	-$31,975

Table 4. Additional cost/acre for preventive practices relative to the industry standard (pruning in December) by region (in 2013 dollars). Values were derived from UCCE cost and return studies, as well as semi-structured interviews with growers, farm advisors, and others knowledgeable in winegrape production in California. Delayed pruning is not costly because it requires the same labor as standard pruning in December.

Region (Crush District number)	Delayed Pruning	Topsin	Double Pruning
Napa (4)	$0	$71	$478
Northern San Joaquin (11)	$0	$45	$175
Central Coast (8)	$0	$90	$243
Lake (2)	$0	$117	$268
Sonoma (3)	$0	$74	$335

Table 5. Additional cumulative discounted net benefits (NB) from adoption of a preventative practice (in 2013 dollars) by region (crush district number) and practice scenario. Note, scenarios with bolded values have positive net benefits over a 25-year lifespan.

	25% DCE			50% DCE			75% DCE		
	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (4)									
Delayed Pruning	**$46,720**	$37,880	$16,159	**$114,680**	**$96,944**	**$44,205**	**$155,303**	**$147,388**	**$89,863**
Topsin	**$45,614**	$36,903	$15,472	**$113,574**	**$95,967**	**$43,517**	**$154,197**	**$146,410**	**$89,175**
Double Pruning	$39,311	$31,334	$11,557	**$107,271**	**$90,397**	$39,603	**$147,894**	**$140,841**	**$85,261**
Northern San Joaquin (11)									
Delayed Pruning	**$12,993**	$10,534	$4,494	**$31,892**	**$26,960**	**$12,293**	**$43,189**	**$40,988**	**$24,990**
Topsin	$11,621	$9,322	$3,642	**$30,520**	**$25,747**	$11,441	**$41,817**	**$39,776**	**$24,138**
Double Pruning	$8,761	$6,795	$1,866	**$27,660**	**$23,221**	$9,665	**$38,957**	**$37,249**	**$22,362**
Central Coast (8)									
Delayed Pruning	**$18,929**	**$15,349**	**$6,548**	**$46,464**	**$39,281**	**$17,912**	**$62,923**	**$59,721**	**$36,412**
Topsin	**$16,401**	**$13,116**	$4,978	**$43,937**	**$37,048**	**$16,342**	**$60,396**	**$57,487**	**$34,842**
Double Pruning	**$13,143**	**$10,236**	$2,954	**$40,679**	**$34,169**	**$14,318**	**$57,137**	**$54,608**	**$32,818**
Lake (2)									
Delayed Pruning	**$12,993**	**$10,534**	$4,494	**$31,892**	**$26,960**	**$12,293**	**$43,189**	**$40,988**	**$24,990**
Topsin	**$11,621**	**$9,322**	$3,642	**$30,520**	**$25,747**	**$11,441**	**$41,817**	**$39,776**	**$24,138**
Double Pruning	**$8,761**	**$6,795**	$1,866	**$27,660**	**$23,221**	**$9,665**	**$38,957**	**$37,249**	**$22,362**
Sonoma (3)									
Delayed Pruning	$23,539	$19,087	$8,142	**$57,781**	**$48,848**	$22,274	**$78,248**	**$74,265**	**$45,280**
Hand painted Topsin	$22,388	$18,070	$7,427	**$56,630**	**$47,831**	$21,559	**$77,097**	**$73,248**	**$44,565**
Double Pruning	$18,347	$14,499	$4,917	**$52,588**	**$44,260**	$19,049	**$73,056**	**$69,677**	**$42,055**

Table 6. Last year infected-untreated vineyard generates positive annual net returns by region.

Region (Crush District number)	Age
Napa (4)	14
Northern San Joaquin (11)	12
Central Coast (8)	12
Lake (2)	13
Sonoma (3)	12

Table 7. Last year mature vineyard generates positive annual net returns, by region (crush district number) and practice scenario.

	25% DCE			50% DCE			75% DCE		
	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (4)									
Delayed Pruning	18	17	16	25	24	19	25	25	25
Topsin	18	17	15	25	24	19	25	25	25
Double Pruning	18	17	15	25	24	19	25	25	25
Northern San Joaquin (11)									
Delayed Pruning	15	15	13	22	20	15	25	25	22
Topsin	15	15	13	22	20	15	25	25	22
Double Pruning	15	14	13	22	20	15	25	25	21
Central Coast (8)									
Delayed Pruning	16	15	14	23	21	16	25	25	24
Topsin	16	15	13	23	21	16	25	25	23
Double Pruning	16	15	13	23	21	16	25	25	23
Lake (2)									
Delayed Pruning	17	16	14	24	22	17	25	25	25
Topsin	17	16	14	24	22	17	25	25	25
Double Pruning	16	16	14	24	22	17	25	25	25
Sonoma (3)									
Delayed Pruning	16	15	13	22	21	16	25	25	23
Topsin	15	15	13	22	20	15	25	25	22
Double Pruning	15	15	13	22	20	15	25	25	22

Table 8. Age when cumulative discounted net benefits of adopting a preventative practice exceeds that of an infected-untreated vineyard, by region (crush district number) and practice scenario.

	25% DCE			50% DCE			75% DCE		
	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (District 4)									
Topsin	6	6	10	5	5	10	4	5	10
Double Pruning	10	9	11	9	8	10	8	8	10
Northern San Joaquin (11)									
Topsin	9	9	10	8	8	10	7	7	10
Double Pruning	11	11	12	10	10	11	10	10	10
Central Coast (District 8)									
Topsin	9	9	10	8	8	10	8	8	10
Double Pruning	11	11	12	10	10	11	10	9	10
Lake (District 2)									
Topsin	7	7	10	6	6	10	6	6	10
Double Pruning	10	10	11	10	9	10	9	9	10
Sonoma (District 3)									
Topsin	7	7	10	6	6	10	6	6	10
Double Pruning	10	10	11	9	9	10	9	9	10

Table 9. Cumulative discounted net benefits for Topsin and Double Pruning adopted at different vineyard ages in a healthy vineyard (in 2013 dollars) by region (crush district number).

	year 3	year 5	year 10
Napa (4)			
Hand painted Topsin	$202,876	$203,005	$203,295
Double Pruning	$196,573	$197,435	$199,380
Northern San Joaquin (11)			
Hand painted Topsin	$31,647	$31,806	$32,167
Double Pruning	$28,787	$29,280	$30,390
Central Coast (8)			
Hand painted Topsin	$56,844	$57,138	$57,802
Double Pruning	$53,586	$54,259	$55,778
Lake (2)			
Hand painted Topsin	$56,021	$56,122	$56,350
Double Pruning	$52,519	$53,028	$54,175
Sonoma (3)			
Topsin	$48,345	$48,479	$48,781
Double Pruning	$44,304	$44,908	$46,271

Table 10. Perceived probability of infection (π) that divides population of growers between non-adopters and adopters for different regions (crush district number) and practice scenarios.

	25% DCE			50% DCE			75% DCE		
	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (4)									
Topsin	0.024	0.026	0.043	0.010	0.010	0.016	0.007	0.007	0.008
Double Pruning	0.159	0.173	0.285	0.065	0.068	0.104	0.048	0.044	0.051
Northern San Joaquin (11)									
Topsin	0.106	0.115	0.190	0.043	0.045	0.069	0.032	0.030	0.034
Double Pruning	0.326	0.355	0.585	0.133	0.139	0.214	0.098	0.091	0.105
Central Coast (8)									
Topsin	0.134	0.146	0.240	0.054	0.057	0.088	0.040	0.037	0.043
Double Pruning	0.306	0.333	0.549	0.125	0.130	0.201	0.092	0.086	0.099
Lake (2)									
Topsin	0.047	0.051	0.084	0.019	0.020	0.031	0.014	0.013	0.015
Double Pruning	0.234	0.255	0.421	0.095	0.100	0.154	0.071	0.066	0.076
Sonoma (3)									
Topsin	0.049	0.053	0.088	0.020	0.021	0.032	0.015	0.014	0.016
Double Pruning	0.221	0.240	0.396	0.090	0.094	0.145	0.066	0.062	0.071

Table 11. Perceived probability of infection (π) that divides population of growers between non-adopters and adopters assuming real discount rate is 0.05. Bolded values denote scenarios where probability falls when discount rate increases.

	25% DCE			50% DCE			75% DCE		
Practice scenario	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (District 4)									
Topsin	0.022	0.024	**0.037**	0.009	0.010	**0.014**	0.007	0.006	0.007
Double Pruning	0.149	0.159	**0.250**	0.063	0.064	**0.093**	0.048	0.043	0.047
Northern San Joaquin (District 11)									
Topsin	0.111	0.117	**0.185**	0.047	0.048	**0.069**	0.035	0.032	0.035
Double Pruning	0.341	0.362	**0.570**	0.145	0.147	**0.213**	0.109	0.099	0.108
Central Coast (District)									
Topsin	0.140	0.149	**0.234**	0.059	0.060	**0.087**	0.045	0.041	0.044
Double Pruning	0.320	0.340	**0.535**	0.136	0.138	**0.200**	0.102	0.093	0.101
Lake (District 2)									
Topsin	0.049	0.052	**0.082**	0.021	0.021	**0.030**	0.016	0.014	0.015
Double Pruning	0.245	0.261	**0.410**	0.104	0.106	**0.153**	0.078	0.071	0.077
Sonoma (District 3)									
Topsin	0.051	0.054	**0.086**	0.022	0.022	**0.032**	0.016	0.015	0.016
Double Pruning	0.231	0.245	**0.386**	0.098	0.100	**0.144**	0.074	0.067	0.073

Appendix A. Parameter Values Used in Simulated Bioeconomic Model

Table A.1. Tons of Cabernet Sauvignon per acre (1 hectare=2.78acres) by year of age and region (crush district number) as reported in associated UCCE Cost and Return Study (UCCE, 2012).

Year of Age	Napa (4)	Northern San Joaquin (11)	Central Coast (8)	Lake (2)	Sonoma (3)
0	0	0	0	0	0
1	0	0	0	0	0
2	1	5	2.5	0.75	1.5
3	4.5	10	5	1.5	3.5
4	4.5	10	7.5	3.5	5
5	4.5	10	7.5	5.75	5

Table A.2. Total Cash Costs per Acre (in 2013 dollars) by year of age and region (crush district number) as reported in the associated UCCE Cost and Return Study, and adjusted to 2013 dollars cost data using the United States Department of Commerce, Bureau of Economic Analysis implicit GDP deflator.

Year of Age	Napa (4)	Northern San Joaquin (11)	Central Coast (8)	Lake (8)	Sonoma (3)
0	$32,303	$12,213	$9,998	$7,301	$26,780
1	$5,264	$3,370	$2,554	$6,942	$4,204
2	$5,304	$1,004	$3,501	$3,252	$5,186
3	$7,784	$3,505	$4,625	$3,404	$6,280
4	$7,784	$3,505	$4,625	$4,053	$6,280
5	$7,784	$3,505	$4,625	$4,053	$6,280

Table A.3. Five-Year Weighted Average Price per ton for Cabernet Sauvignon (in 2013 dollars) as reported in the United States Department of Agriculture, National Agricultural Statistical Service's Annual Crush District Reports, and adjusted to 2013 dollars using the United States Department of Commerce, Bureau of Economic Analysis implicit GDP deflator.

Year of Age	Napa (4)	Northern San Joaquin (11)	Central Coast (8)	Lake (2)	Sonoma (3)
2014	$5,837	$643	$1,444	$1,981	$2,578
2013	$5,470	$700	$1,377	$1,724	$2,461
2012	$5,127	$737	$1,314	$1,636	$2,345
2011	$4,812	$637	$1,155	$1,410	$2,182
2010	$4,716	$532	$1,022	$1,363	$2,206
Average	**$5,192**	**$650**	**$1,262**	**$1,623**	**$2,355**

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