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## Article

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# Identifying economic hurdles to early adoption of preventative practices: The case of trunk diseases in California winegrape vineyards<sup>☆</sup>

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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 winegrape production in select counties of California and find widespread benefits from early adoption, increasing vineyard profitable lifespans, in some cases, by close to 50%. However, hurdles 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. Development of extension resources communicating benefits and potential hurdles to growers likely reduces uncertainty, increasing early adoption. Improvements in efficacy of preventative practices, perhaps by detecting when pathogen spores are released into the vineyard, will increase early adoption. Lastly, practice cost reductions will increase early adoption too, especially when the time it takes for adoption to payoff and infection uncertainty are influential in adoption decisions.

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**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.

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For all of these diseases, the causal agents are fungi that establish chronic infections of the wood, which represent mixtures of different trunk pathogens (Bruez et al., 2016); rarely is one trunk disease present in a vineyard. 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, 2013). As these practices are preventative in nature, they must be used before vines are infected to ensure optimal efficacy.<sup>1</sup>

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., 2015). 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).<sup>2</sup> 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 a vineyard is 8 years old or older; 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. Reluctance to adoption early may also stem from how long it takes for the symptoms to appear in the vineyard. The relatively long time it takes for the disease to grow in a vineyard implies annual benefits from early adoption will take many years to accumulate and offset the annual additional cost of the practice, which is incurred immediately.

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 winegrape growing counties, which are aligned with Grape Pricing Districts or 'crush districts' as follows: Napa (Crush District 4), San Joaquin (Crush District 11), Central Coast (Crush District 8), Lake (Crush District 2), and Sonoma (Crush District 3).<sup>3</sup> Our parameters include disease-control efficacies from published experimental field 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 counties. Also, it is the cultivar most widely considered in the published University of California Cooperative Extension (UCCE) Cost & Return studies (UCCE, 2004–2014), which form the basis for the economic analysis. We derive annual net returns for a healthy vineyard 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 gains or losses due to adopting in young vineyards rather than waiting until year 10 to do so.

## 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; 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

<sup>1</sup>Although, in general preventative practices prevent secondary infections in an infected vineyard and re-infection in a vineyard where vine surgery is performed, here it refers to preventing prevent infection of new pruning wounds on vines with infections that started at pruning wounds in the past given vines are pruned every dormant season; each year there is a new set of wounds.

<sup>2</sup>Recommendations to use preventative practices after the disease is meant to reduce secondary infections.

<sup>3</sup>Winegrape growing areas within California have been delineated in a variety of ways. In addition to counties or crush district, others (such as Alston et al. (2015)) have delineated regions based on variety and value. Table 4 shows these regions as well.

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, 2014; Ricketts et al., 2015), given that field experiments would take decades to complete. Like these past studies, we establish baseline conditions and scenarios to capture the dynamics of trunk disease infections and net returns in the different winegrape districts using information on currently available practices, their costs, and effects on yields and lifespan taken from the UCCE Cost & 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 on plant pathology and the efficacy of pruning practices, and interviews with winegrape growers, farm advisors, and other stakeholders. 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) in young vineyards, relative to adopting in year 10 when symptomatic vines are visible. We examine changes in returns and costs to the grower over a 25-year vineyard lifespan, holding all other factors constant except practice costs and yield losses from adopting preventative practices in young vineyards relative to returns and costs from adopting when a vineyard is 10 years old. 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.

An important factor in studying winegrapes in California is the regional variation in yield and price per ton (see Table 2 for parameter value details). For example, at one extreme in Napa and Sonoma Counties (Crush Districts 4 and 3, respectively), establishment decisions and management practices restrict vineyard yields (approximately 4.5 to 5 t of Cabernet Sauvignon per acre in mature vineyards) with the goal of achieving higher wine quality that sells at a high average price per ton (\$2,355 and \$5,192 for Sonoma and Napa, respectively). At the other extreme, in San Joaquin county (Crush District 11), fruit prices are much lower (\$650 per ton) and vineyards produce higher yields (10 t per acre (CDFA/NASS, 2015)). The other counties 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 3). DCE is the proportion of pruning wounds which do not become infected as a result of a preventative practice but would otherwise become infected. 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 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 M against *Phaeomoniella chlamydospora* versus 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.

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 M	Topsin M 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 M by hand with a paintbrush or sponge to cover pruning wounds. <sup>a</sup>

<sup>a</sup>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 M is also registered for spray application.

Table 2

Parameters used in simulated economic analysis.

Additional cost/acre (in 2013 dollars) for preventive practices relative to industry winter pruning standard by county.<sup>a</sup> Source: UCCE cost and return studies and semi-structured interviews with growers, viticulture advisors, and other stakeholders in California winegrape production.

	Practice		
	Delayed Pruning	Topsin M	Double Pruning
Napa (4)	\$0	\$71	\$478
San Joaquin (11)	\$0	\$90	\$243
San Luis Obispo (8)	\$0	\$117	\$268
Lake (2)	\$0	\$90	\$279
Sonoma (3)	\$0	\$74	\$335

Tons/acre of Cabernet Sauvignon by age and county. Source: UCCE Cost and Return Studies.

	Vineyard Age					
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5 +
Napa (4)	0	0	1	4.5	4.5	4.5
San Joaquin (11)	0	0	5	10	10	10
San Luis Obispo (8)	0	0	2.5	5	7.5	7.5
Lake (2)	0	0	0.75	1.5	3.5	5.75
Sonoma (3)	0	0	1.5	3	5	5

Total cash costs/acre (2013 dollars) by age and county. Source: UCCE Cost and Return Studies

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5 +
Napa (4)	\$32,303	\$5,264	\$5,304	\$7,784	\$7,784	\$7,784
San Joaquin (11)	\$12,213	\$3,370	\$3,395	\$3,505	\$3,505	\$3,505
San Luis Obispo (8)	\$9,998	\$2,554	\$3,501	\$4,625	\$4,625	\$4,625
Lake (2)	\$7,301	\$6,942	\$3,252	\$3,404	\$4,053	\$4,053
Sonoma (3)	\$26,780	\$4,204	\$5,186	\$6,280	\$6,280	\$6,280

Five-year weighted average price/ton for Cabernet Sauvignon (2013 dollars)  
Source: USDA/NASS Annual Crush District Reports (USDA-NASS 2015)

Napa (4)	\$5,192
San Joaquin (11)	\$650
San Luis Obispo (8)	\$1,262
Lake (2)	\$1,623
Sonoma (3)	\$2,355

Remaining Parameter Values

	Symbol	Value	Ref.
Carry Capacity	$K$	0.92	Duthie et al. (1991)
Initial Percentage of Symptomatic Vines	$Y_0$	0.001	Duthie et al. (1991)
Constant of Integration	$B_0 = (K - Y_0)/Y_0$	919	Duthie et al. (1991)
Simulation Constants of Integration ( $B_{age}$ )	$B_3$	305.9085	Derived from Eq. (1)
	$B_5$	58.7497	Derived from Eq. (1)
	$B_{10}$	7.46919	Derived from Eq. (1)
Trunk Disease Growth Rate	$g_0$	0.55	Duthie et al. (1991)
Real Discount Rate	$\delta$	0.03	Fuller et al. (2014) Fuller et al. (2015)

<sup>a</sup>All dollar amounts adjusted to 2013 dollars using the United States Department of Commerce, Bureau of Economic Analysis implicit GDP deflator (USDC-BEA 2015).

Table 3

Disease control efficacies (DCEs; % pruning wounds protected) for preventative practices against three trunk diseases and six trunk pathogens.

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

<sup>a</sup>For Topsin M, 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.

<sup>b</sup>When applied to Chardonnay in 2005 and Zinfandel in 2006; averaged across both cultivars/years (Rolshausen et al., 2010).

<sup>c</sup>When applied to Chardonnay (Amponsah et al., 2012).

<sup>d</sup>When pruning Cabernet Sauvignon and Chardonnay in March versus December, in 2007 and 2008 (Urbez-Torres and Gubler, 2011).

<sup>e</sup>When pruning Cabernet Sauvignon in March versus January, in 1997 and 1998 (Larignon and Dubos, 2000).

<sup>f</sup>When pruning Grenache in March versus December (Petzoldt et al., 1981).

<sup>g</sup>When pruning Chardonnay and Merlot in February versus December, in 2001 and 2002 (Weber et al., 2007).

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 early adoption scenarios with that of year 10, and measure the changes in costs and returns not just today, but in the future as well.

### 3.1. Biological model

To approximate the spread of trunk diseases and corresponding yield effects throughout the vineyard, we adopt the trunk disease logistic growth model estimated by Duthie et al. (1991) using test plots of Chenin blanc and Barbera varietals grown throughout Merced County, California. The yield loss function comes from Munkvold et al. (1994), who derived yield losses due to the combined effect of Eutypa and Botryosphaeria Diebacks from the same test plots as used in Duthie et al. (1991). Although we do not explicitly model the infectious disease in a susceptible, infected, and recovered model [see Atallah et al. (2014), for example], we rely on the plant pathology and infectious disease literature which provides numerous empirical studies using the logistic function to capture the spread of infection.<sup>4</sup> Following the estimates in Duthie et al. (1991), it is assumed that 92% of vines are susceptible when first planted, declining over time as the percentage of infected vines grows. In addition, because trunk diseases go many years before detection, removal of infected vines when pruning slows the spread of the infection but cannot eradicate it. We apply this relationship to Cabernet Sauvignon grown in the sample regions 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

$$Y_t = \frac{K}{(1 + B_0 e^{-g_0 t})} = \frac{0.92}{(1 + 919 e^{-0.55t})} \quad (1)$$

where  $Y_t$  is the percentage of symptomatic vines per acre,  $K$  is the carrying capacity,  $t$  is the age of the vineyard,  $B_0$  is the constant of integration and equals  $(K - Y_0)/Y_0$ , where  $Y_0$  is the initial percentage of symptomatic vines is set at 0.001. Lastly,  $g_0$  is the growth rate. Fig. 1 shows this growth over the 25-year lifespan evaluated in the empirical analysis.<sup>5</sup>

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 growth rate estimated by Duthie et al. (1991) represents the average scenario, in a

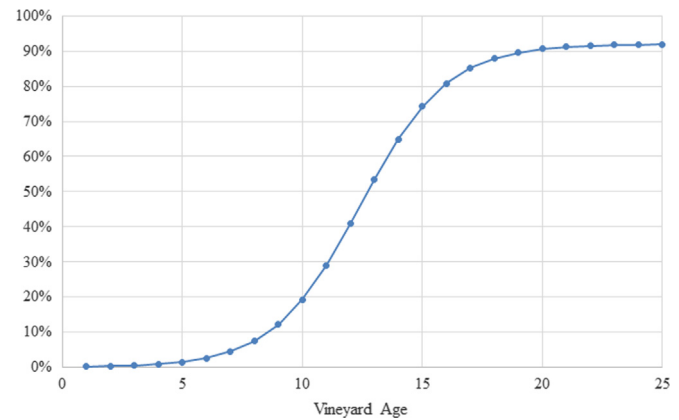


Fig. 1. Trunk Disease incidence (in % symptomatic vines/acre by the age of the vineyard (Duthie et al. 1991). Note: Duthie et al. (1991) measured Eutypa dieback symptoms and dead spur positions, the latter of which is now known as a general symptom of three trunk diseases (Botryosphaeria dieback, Eutypa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

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

$$Yield_t^I = (100.1 - 98.81Y_t) * Yield_t^H \quad (2)$$

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. Fig. 2 illustrates reduction in yields as disease incidence increases for one of the winegrape growing counties.<sup>6</sup> How preventative practices affect this relationship is discussed below. Yield per acre values for the different counties used in the empirical analysis are contained in Table 2 above.

### 3.2. Economic model

When deciding whether to adopt one practice over another, 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

<sup>4</sup>Numerous examples from the literature use or suggest the use of a logistic growth function to capture the disease growth (e.g., Madden et al., 2000; Murphy et al., 2016)

<sup>5</sup>This lifespan is consistent with California winegrape production as reported in the UCCE Cost and Return Studies.

<sup>6</sup>Figures showing the effect of trunk diseases in other regions are available on request. Note, the percentage change in yield is the same for all counties, however, different counties yield different tons per acre and thus we will see different absolute reductions but not relative reductions.

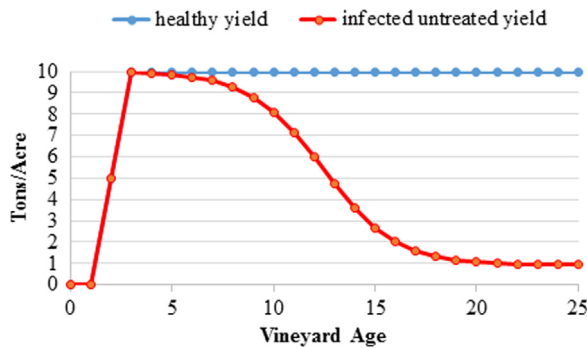


Fig. 2. Effect of Trunk Diseases on yield by vineyard age in a Cabernet Sauvignon vineyard in San Joaquin County. Note: Effect of infection on yield from Munkvold et al. (1994). Yield data come from UCCE (2012).

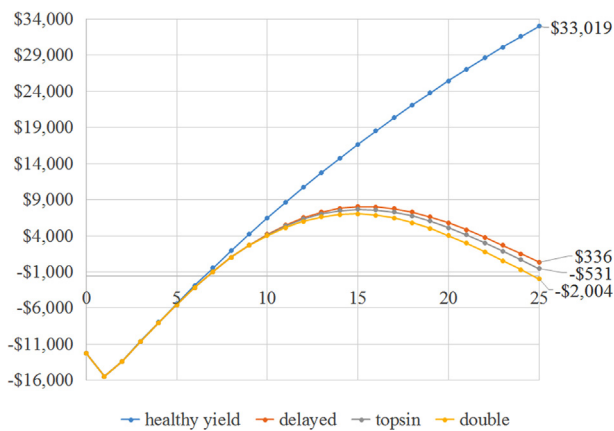


Fig. 3. Cumulative undiscounted net returns (Total Revenue – Total Cost) per acre for healthy versus infected-untreated Cabernet Sauvignon vineyards in San Joaquin County (in 2013 dollars).

net returns per acre (NR) are defined as

$$NR_t(A, c, dce) = Price_t \times Yield_t(A, dce) - Cost_t(A, c) \quad (3)$$

where  $A$  denotes the age when adoption occurs,  $c$  the annual preventative practice cost,  $dce$  the DCE, and  $t$  the age of the vineyard. Fig. 3 shows streams of net returns in 2013 dollars over a 25-year vineyard lifespan for the San Joaquin County. A grower with a healthy vineyard versus one with an infected-vineyard that adopts preventative practices in year 10 with 50% DCE can expect to make \$33,019 per acre instead of between \$336 and -\$2,004, depending on the different practice costs, 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 and evaluate years of lost profits for a given initial investment.

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

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

Table 4

Cumulative discounted net benefits (NB) per acre (in 2013 dollars) for healthy and infected-untreated vineyards over a 25-year lifespan, by county (crush district number).

County (Crush District number)	Region <sup>a</sup>	Healthy vineyard	Infected-untreated vineyard
		NB per acre	
Napa (4)	North Coast	\$203,982	\$42,271
San Joaquin (11)	North Central Valley	\$33,019	-\$11,957
San Luis Obispo (8)	Central Coast	\$59,372	-\$6,144
Lake (2)	Other California	\$40,375	-\$4,601
Sonoma (3)	North Coast	\$49,496	-\$31,975

<sup>a</sup>These winegrape-growing regions are based on value and variety as delineated in Alston et al. (2015).

Table 4 shows NB per acre when the real discount rate ( $\delta$ ) is assumed to be 3%,<sup>7</sup> for a healthy vineyard and an infected-untreated vineyard, across the five counties 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. As noted in Hillis et al. (2015), many growers adopt preventative practices once trunk disease is apparent. PCAs also tend to recommend these preventative practices more often in vineyards with a greater percentage of symptomatic vines (Hillis et al., 2015). As such, \$160,000 per acre is an upper bound on potential losses over the 25 years. Other growers, alternatively, 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 hopefully restore yields) before the 25 years have passed. This latter approach to managing trunk diseases can be prohibitively costly and not guaranteed to restore yields as the replanted vine or retrained sucker may be infected, or the remaining vine may not produce suckers. Given the scope of this analysis is to understand why growers do not adopt preventative practices in young vineyards before symptoms are apparent, we leave the evaluation of vine surgery and replanting for future analysis.

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

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

where the superscripts denote healthy or infected vineyards, respectively, and  $\pi$  is the grower's perceived probability of infection. Fig. 4 shows  $E[NB(\cdot)]$  for a known preventative practice adopted in a 10-year old vineyard ( $A_{10}$ ) and a 5 years old vineyard ( $A_5$ ), for different perceived probabilities of

<sup>7</sup>Fuller et al. (2014, 2015) also assume a 3% real discount rate. However, the literature provides a range of values for the discount rate. Some as high as 5.75%. In our analysis we considered other discount rates and found no qualitative change in results.

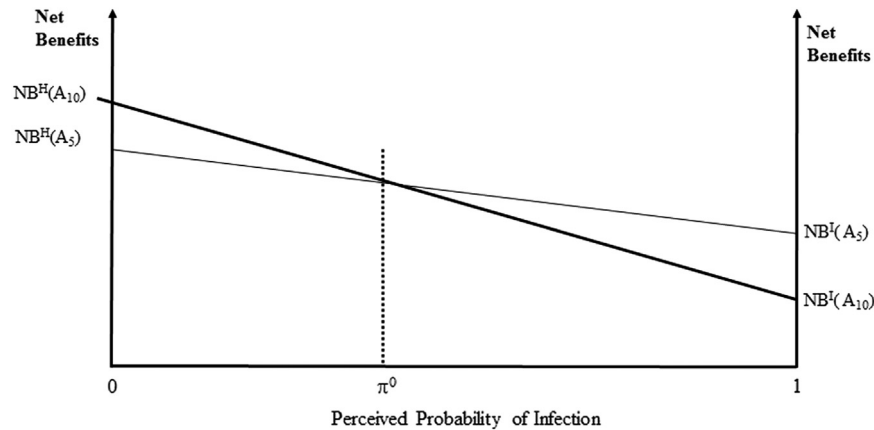


Fig. 4. Expected net benefits for infected-untreated scenario and representative adoption scenario as a function of grower perception of disease risk. The probability  $\pi^0$  separates growers into adopters with perceived probabilities of infection greater than  $\pi^0$  and non-adopters with perceived probabilities of infection less than  $\pi^0$ .

infection ( $\pi$ ). 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 ( $A, c, dce, \delta$ ) given their knowledge of costs and returns, and perception of disease infection. This model also provides an infection probability threshold ( $\pi^0$ ) 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  $\pi^0$ , 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  $\pi^0$ , they would be expected to wait until year 10 to adopt a practice, those with a perceived probability of infection greater than  $\pi^0$  would adopt in year 5, and those at  $\pi^0$  would be indifferent. Over time, grower perceptions of the probability of infection will likely increase as a result of experiential or scientific evidence, extension services, or networking, and thus a greater share of growers would be expected to adopt in the future as well.

We derive a general expression for  $\pi^0$  that divides adopters and nonadopters by equating the expected net benefits from adopting in year 10

$$E[NB(A_{10}, c, dce, \delta)] = (1 - \pi)NB^H(A_{10}, c, dce, \delta) + \pi NB^I(A_{10}, c, dce, \delta), \quad (6)$$

with the expected net benefits from adopting a practice in year  $y$ , which is earlier than year 10

$$E[NB(A_y, c, dce, \delta)] = (1 - \pi)NB^H(A_y, c, dce, \delta) + \pi NB^I(A_y, c, dce, \delta) \quad (7)$$

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

$$E[NB(A_y, c, dce, \delta)] = (1 - \pi)[NB^H(A_{10}, \delta) - C(A_y, c, \delta)] + \pi[NB^I(A_y, c, dce, \delta)] \quad (8)$$

where  $C(A, c, \delta)$  are the cumulative discounted practice costs

over the additional years of adoption, which increases with decreases in  $A$  and  $\delta$ , and increases in  $c$ , while  $NB(\cdot)$  increases with increases in  $dce$  and decreases in  $A$ ,  $c$ , and  $\delta$ .<sup>8</sup> Solving for  $\pi^0$  produces the general expression

$$\pi^0(A_y, c, dce, \delta) = \frac{C(A_y, c, \delta)}{NB^I(A_y, c, dce, \delta) - NB^I(A_{10}, c, dce, \delta) + C(A_y, c, \delta)} \quad (9)$$

that varies with changes in the age of the vineyard when early adoption occurs ( $A_y$ ), practice cost ( $c$ ), disease control efficacy ( $dce$ ), or the discount rate ( $\delta$ ). Evaluating the comparative statics with respect to these factors shows: 1) when vineyard age at time of adoption changes, the change in  $\pi^0$  and the proportion of adopters is ambiguous, suggesting that adopting earliest may not be optimal; 2) when practice costs increase,  $\pi^0$  increases, reducing the share of adopters; 3) when  $dce$  increases, the change in  $\pi^0$  is ambiguous; and 4) when  $\delta$  changes, the change in  $\pi^0$  is also ambiguous.

To see this, we first take the derivative of the equilibrium condition with respect to  $A$ , yielding<sup>9</sup>

$$\frac{\partial \pi(A_y)}{\partial A_y} = \frac{\frac{\partial C(A_y)}{\partial A_y} [NB^I(A_y) - NB^I(A_{10}) + C(A_y)] - C(A_y) \left[ \frac{\partial NB^I(A_y)}{\partial A_y} + \frac{\partial C(A_y)}{\partial A_y} \right]}{[NB^I(A_y) - NB^I(A_{10}) + C(A_y)]^2} \quad (10)$$

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

$$\frac{\partial C(A_y)}{\partial A_y} [NB^I(A_y) - NB^I(A_{10}) + C(A_y)] - C(A_y) \left[ \frac{\partial NB^I(A_y)}{\partial A_y} + \frac{\partial C(A_y)}{\partial A_y} \right] < 0 \quad (11)$$

<sup>8</sup>Note,  $C(\cdot)$  appears in the first term on the right-hand side of Eq. (8) but not the second as it is part of  $NB^I(A, c, dce, \delta)$ . We do so to provide a simpler depiction of the infection probability threshold and easier interpretation of the comparative static results.

<sup>9</sup>Some subscripts are removed to simplify presentation.



Rearranging terms yields,

$$\frac{\frac{\partial C(A_y)}{\partial A_y}}{C(A_y)} < \frac{\left[ \frac{\partial NB^I(A_y)}{\partial A_y} \right]}{[NB^I(A_y) - NB^I(A_{10})]} \quad (12)$$

When the percentage increase in the cost of the practice (given it is adopted sooner rather than later) when the vineyard is healthy is less than (greater than) the percentage increase in the net benefits from adopting earlier when it is infected, then the threshold will fall (rise). This shows theoretically that a grower acting in their best interest may not adopt at the earliest possible vineyard age. 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.

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

$$\frac{\partial \pi(c)}{\partial c} = \frac{\frac{\partial C(A_y, c)}{\partial c} [NB^I(A_y, c) - NB^I(A_{10}, c) + C(A_y, c)] - C(A_y, c) \left[ \frac{\partial NB^I(A_y, c)}{\partial c} \right]}{[NB^I(A_y, c) - NB^I(A_{10}, c) + C(A_y, c)]^2} > 0 \quad (13)$$

we see the potential share of growers who adopt falls as the threshold moves outward from zero, given the first term in the numerator of Eq. (13) 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 increase, the change in  $\pi^0$  is ambiguous as both terms inside the brackets in the numerator of Eq. (14) are positive.

$$\frac{\partial \pi(A)}{\partial dce} = \frac{-C(A, c) \left[ \frac{\partial NB^I(A_y, c, dce)}{\partial dce} - \frac{\partial NB^I(A_{10}, c, dce)}{\partial dce} \right]}{[NB^I(A_y, c) - NB^I(A_{10}) + C(A_y, c)]^2} \quad (14)$$

An increase in DCE results in an increase in  $\pi^0$  (and a decrease in earlier adoption) when

$$\frac{\partial NB^I(A_y, c, dce)}{\partial dce} < \frac{\partial NB^I(A_{10}, c, dce)}{\partial dce} \quad (15)$$

That is, when the cumulative discounted net benefits for a vineyard that adopts preventative practices in mature vineyards increase more than those in a vineyard that adopts earlier, we would see a movement toward later adoption. This relationship becomes more apparent when comparing adoption in earlier and earlier years since the net benefits from adopting earlier and earlier decline given the slow initial growth in the infection. Further, when  $dce$  is high and increases, we might expect the condition in 15 to hold since the nature of the disease growth means adopting earlier is likely to produce fewer additional benefits than when we adopt late.

Lastly, we consider a change in  $\delta$ , reflecting both changes in a grower's time preference as well as differences in growers' time preferences, as growers are not all likely to have the same intertemporal preferences. The comparative static with respect to  $\delta$  is

$$\frac{\partial \pi(\cdot)}{\partial \delta} = \frac{\frac{\partial C(\cdot)}{\partial \delta} [NB^I(A_y) - NB^I(A_{10}) + C(\cdot)] - C(\cdot) \left[ \frac{\partial NB^I(A_y)}{\partial \delta} - \frac{\partial NB^I(A_{10})}{\partial \delta} + \frac{\partial C(\cdot)}{\partial \delta} \right]}{[NB^I(A_y) - NB^I(A_{10}) + C(A)]^2} \quad (16)$$

and given the decrease in  $\frac{\partial NB^I(A_y)}{\partial \delta}$  is greater than the decrease in  $\frac{\partial NB^I(A_{10})}{\partial \delta}$ , the two products in the numerator are both negative. To determine the sign we set the numerator less than zero and solve

$$\frac{\partial C(\cdot)}{\partial \delta} [NB^I(A_y) - NB^I(A_{10}) + C(\cdot)] - C(\cdot) \left[ \frac{\partial NB^I(A_y)}{\partial \delta} - \frac{\partial NB^I(A_{10})}{\partial \delta} + \frac{\partial C(\cdot)}{\partial \delta} \right] < 0 \quad (17)$$

Rearranging terms yields,

$$\frac{\frac{\partial C(\cdot)}{\partial \delta}}{C(\cdot)} < \frac{\left[ \frac{\partial NB^I(A_y)}{\partial \delta} - \frac{\partial NB^I(A_{10})}{\partial \delta} \right]}{[NB^I(A_y) - NB^I(A_{10})]} \quad (18)$$

When the percentage decrease in the cost of the practice is less than (greater than) the percentage decrease in the net benefits, then the threshold will fall (rise) with a change in the discount rate. The long term nature of the effect of the disease on 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 additional costs, then we would expect that an increase in the discount rate decreases  $\pi^0$ , and vice versa.

Without knowing the distribution for grower perceptions of the 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 might assume most growers perceive the probability of infection to be relatively close to 1, based on the findings of Hillis et al. (2015), that PCAs report many vineyards have trunk disease. Nonetheless, this may not be the case as the PCAs are not recommending preventative practices until after the disease is apparent and some growers may be relatively new to the industry and thus have not yet seen the effects or prevalence of trunk disease. We see, in the empirical analysis to follow, that  $\pi^0$  is, in many cases, very close to zero. These low values and lack of early adoption suggests another reason is likely compelling growers to wait to adopt.

### 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

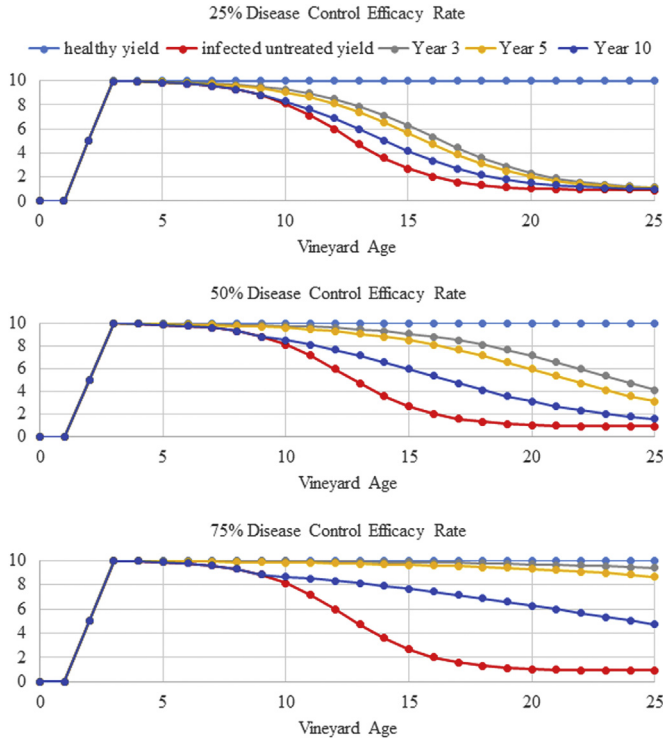


Fig. 5. Tons/acre for different ages of adoption and disease control efficacy for a San Joaquin County Cabernet Sauvignon vineyard.

(UCCE, 2004–2014) and historical price data gathered from California grape crush reports published annually by USDA–NASS. Price and cost 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, 2014) and Fuller et al. (2014, 2015). Each scenario has the same cultural practices, but differs by winter pruning practice and the additional cost associated with the practice (see Table 2). 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. We are also able to compare results across practice costs and DCE to identify potential gains from investing in lowering costs or raising DCE.

The baseline model for each district simulates production from a healthy vineyard and then one infected with trunk disease. 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

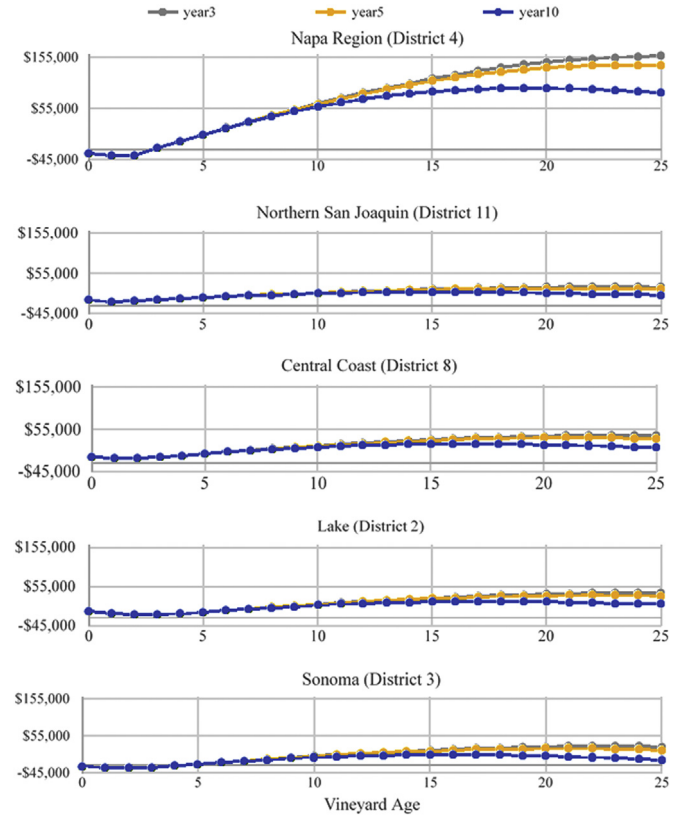


Fig. 6. Cumulative discounted net returns for 50% disease control efficacy delayed pruning adopted at different vineyard ages for all counties.

change in disease incidence by reducing the increasing percentage of symptomatic vines and restarting the time step to reflect the new path as follows

$$Y_t = \begin{cases} \frac{AK}{(1 + B_0 e^{-C_{80}(t)})} & \text{if } t < \text{age} \\ \frac{AK}{(1 + B_{\text{age}} e^{-(dce * g_0(t - \text{age}))})} & \text{if } t \geq \text{age} \end{cases} \quad (19)$$

where  $B_{\text{age}} = (K - Y_{\text{age}})/Y_{\text{age}}$  and  $Y_{\text{age}}$  is the percentage of symptomatic vines at the time adoption begins.<sup>10</sup>

#### 4. Results and discussion

The effects of these preventative practices on yield, when adopted at different ages, are shown in Fig. 5 for a representative San Joaquin County vineyard.<sup>11</sup> 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.

Fig. 6 shows the effect on cumulative discounted net returns of adopting delayed pruning in an infected vineyard at

<sup>10</sup>For the simulation model  $B_{\text{age}}$  equals 305.9085, 58.7497, and 7.469187 for adoption in year 3, 5, and 10, respectively, given the logistic growth model specified in Eq. (1).

<sup>11</sup>As noted previously, the percentage change in yield is constant across counties, however, different counties yield different tons per acre (see Table 4) and have different cultural and practice costs.

Table 5

Additional cumulative discounted net benefits (NB) per acre from adoption of a preventative practice (in thousands of 2013 dollars) with a 50% disease control efficacy rate, by county (crush district number) and practice scenario relative to adoption in year 10. Note, scenarios with bolded values have negative cumulative net benefits over a 25-year lifespan.

	Year 3	Year 5	No Action
Napa (4)			
Delayed Pruning	\$70.48	\$52.74	–\$44.21
Topsin M	\$70.06	\$52.45	–\$43.52
Double Pruning	\$67.67	\$50.79	–\$39.60
San Joaquin (11)			
Delayed Pruning	\$19.60	\$14.67	–\$12.29
Topsin M	\$19.08	\$14.31	–\$11.44
Double Pruning	\$18.00	\$13.56	–\$9.67
San Luis Obispo (8)			
Delayed Pruning	\$28.55	\$21.37	–\$17.91
Topsin M	\$27.60	\$20.71	–\$16.34
Double Pruning	\$26.36	\$19.85	–\$14.32
Lake (2)			
Delayed Pruning	\$28.13	\$21.06	–\$17.66
Topsin M	\$27.60	\$20.70	–\$16.79
Double Pruning	\$26.49	\$19.93	–\$14.97
Sonoma (3)			
Delayed Pruning	\$35.51	\$26.57	–\$22.27
Topsin M	\$35.07	\$26.27	–\$21.56
Double Pruning	\$33.54	\$25.21	–\$19.05

Table 6

Last year mature vineyard generates positive annual net returns, by county (crush district number) and practice scenarios with a 50% DCE.

	Year 3	Year 5	Year 10
Napa (4)			
Delayed Pruning, Topsin M, Double Pruning	25	24	19
San Joaquin (11)			
Delayed Pruning, Topsin M, Double Pruning	22	20	15
San Luis Obispo (8)			
Delayed Pruning, Topsin M, Double Pruning	23	21	16
Lake (2)			
Delayed Pruning, Topsin M, Double Pruning	24	22	17
Sonoma (3)			
Delayed Pruning	22	21	16
Topsin M, Double Pruning	22	20	15

reduction in the cost of the practice increases net benefits considerably less than increases in the DCE rate, suggesting advances in DCE rates may do more to increase early adoption than lowering the cost.

Note, these results assume growers continue to operate their vineyards the entire 25-year lifespan, which is in line with past economics studies (Alston et al., 2013, 2014; Fuller et al., 2015., 2014; Tumber et al., 2014), evidence from the field, and from discussions with growers, advisors, and others involved in winegrape production. It is possible they will retrain or replant a vineyard before the 25 year period ends but to understand the effect of trunk diseases on a vineyard's lifespan we evaluate costs and benefits over the entire 25 years.

We observe 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 an infected vineyards in which preventative practices with 50% DCE are adopted when the vineyard is 10 years old are likely to be cut by as much as 40%. The greatest losses in years of profitable net returns is seen in San Joaquin and Sonoma Counties. Lake and Central Coast are similarly disadvantaged. Napa with its larger profit margin experience the lowest decline in years of profitability.

We also see that when preventative practices are adopted earlier the number of years a grower can expect positive net returns increases. More specifically, the data suggest that adoption at the earliest vineyard age we consider (3 years old) provides up to 7 years of additional positive net returns. The profitable lifespan for Napa reaches 25 years – the maximum age of a vineyard. Other regions only see one to three years of negative net returns. Adoption at 5 years old results in one to two fewer years of positive net returns than the 3-year old scenarios. Results for the other DCE rates are shown in Appendix Table A.2. 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). Nonetheless, with such a high DCE rate, losses are at a minimum and thus adopting earlier increases net returns significantly but not the number of years of positive net

different ages, assuming a 50% DCE for the five counties. The sooner the practice is adopted, the greater the net benefits across the regions but at a declining rate. We also see the benefits from adopting early are greatest in Napa, where the price per ton is greatest while yield per acre the lowest. The gains in San Joaquin from early adoption are lowest. In this county, prices are the lowest and the highest yield per acre. We can also see that the economic incentive to adopt in year 3 in this county is nearly nonexistent. The other three counties have relatively similar results and fall within these two bounds. The advantage to adopting early will be affected by DCE and practice costs and as these graphs depict a 50% DCE rate costless alternative, the benefits deviate with changes in these factors as seen in the Tables 5 and A.1. Table 5 contains the cumulative discounted net benefits for each 50% DCE scenario relative to adopting when the vineyard is 10 years old. In all scenarios, the greatest net benefits occur when a practice is adopted in year 3.<sup>12</sup> The bolded values in Table 5 reflect negative cumulative net benefits for the corresponding scenario. Adopting in year 5 in Sonoma is not profitable over the entire 25-year lifespan. At this DCE rate (50%), many of the year 10 scenarios also generate positive benefits over the vineyard lifespan, except for Sonoma, and hand painting Topsin M or double pruning in San Joaquin.<sup>13</sup> When we compare across practice costs and DCE rates we see that

<sup>12</sup>Results for the other DCE scenarios can be found in Table A.1.

<sup>13</sup>When DCE is 25% many of the year 10 scenarios do not generate positive returns over the 25-year lifespan (see Table A.1).

Table 7

Years until cumulative discounted net benefits of adopting a preventative practice exceeds those from an infected-untreated vineyard, by county (crush district number) and 50% DCE practice scenario.

	Year 3	Year 5	Year 10
Napa (District 4)			
Topsin M	2	0	0
Double Pruning	6	3	0
San Joaquin (11)			
Topsin M	5	3	0
Double Pruning	7	5	1
San Luis Obispo (District 8)			
Topsin M	5	3	0
Double Pruning	7	5	1
Lake (District 2)			
Topsin M	3	1	0
Double Pruning	7	4	0
Sonoma (District 3)			
Topsin M	3	1	0
Double Pruning	6	4	0

returns. When the DCE is only 25%, adoption at any age does little to curb the years of negative net returns. As when DCE is 75%, adopting earlier with a practice with a 25% DCE rate does little to curb losses, increasing the number of years of positive net returns by a couple of years at best. We also see that lower practice costs (as seen with delayed or hand-painted Topsin M relative to double pruning) do little to alter the profitable lifespan. DCE, as noted above, can make a considerable difference in a vineyard's profitable lifespan, further suggesting that improvement in DCE may increase early adoption more than reductions in practice costs.

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.<sup>14</sup> 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 number of years it takes a vineyard that adopts at ages 3, 5, and 10 to outperform, in terms of cumulative discounted net benefits, an infected-untreated vineyard shown in Tables 7 and A.3, we see that nearly every

practice adopted in year 10 pays for itself immediately, regardless of county.<sup>15</sup>

However, when Topsin M is hand-painted on pruning wounds starting when the vineyard is 3 years old, it can take between 2 (Napa) and 5 years (San Joaquin and Central Coast) to outperform an infected-untreated vineyard. When this practice is adopted in year 5, Napa vineyards may outperform immediately. Lake and Sonoma vineyards may take one to two years to outperform an infected-untreated vineyards. If the more expensive double pruning is adopted in year 3, it may take upwards of 7–8 years to outperform an infected-untreated vineyard. We also see adoption in year 5 outperforms no action at roughly the same age as adopting in year 3 given the two year difference in values for years 3 and 5 in Tables 7 and A.3. When double pruning has 75% DCE, we see the first indication that growers may have an incentive to adopt later. In two (Napa and Lake) of the five regions (at the 50% DCE rate), the age when a practice outperforms no action is sooner when adopted in year 5 than when adopted in year 3. These results suggest that a grower may be reluctant to adopt a preventative practice because they fail to see its effectiveness or perceive it to be ineffective given the long time it takes to outperform an infected untreated vineyard while practices adopted in year 10 tend to pay off immediately.

Furthermore, increasing DCE or reducing the cost of a practice appear to have similar effects on a practice's payoff potential. A comparison of results in Tables 7 and A.3 show similar reductions in this measure. As such we might expect investments in either improved DCE or lower costs will have a similar effect on early adoption when the time it takes to pay off the adopted practice is an important hurdle to adoption.

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 influence the decision to adopt early. If this probability is sufficient close to one, it would help explain why growers wait to adopt preventative practices until after symptoms appear. 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. Estimates of the infection probability threshold ( $\pi^0$ ), in Eq. (9) above are displayed in Tables 8 and A.4.

The difference in the cost of the practices heavily influences the estimated probabilities. Topsin M, which is less costly than double pruning, has noticeably lower probabilities than double pruning, suggesting a relatively higher rate of early adoption, irrespective of county. When practice cost is higher, as with double pruning, the estimated perceived probability ( $\pi^0$ ) is closer to 1 but still far from it, implying that the share of growers who adopt earlier should still be greater than we see. Further, when grower perception of DCE is high, we see in

<sup>14</sup>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. Furthermore, even though the additional cost of the delayed pruning above and beyond conventional winter pruning is zero the calculations still capture the opportunity cost of conventional pruning as embodied in the annual cultural costs used in the analysis.

<sup>15</sup>We compare these results to the case on an infected-untreated vineyard since it better illustrates how long each practice takes to pay for itself as opposed to comparing results to the year 10 returns.



Table 8

Infection probability threshold ( $\pi^0$ ) that divides population of growers between adopters in year 10 and earlier adopters for different regions (crush district number) and 50% DCE practice scenarios.

	50% DCE	
	Year 3	Year 5
Napa (4)		
Topsin M	0.01	0.01
Double Pruning	0.04	0.04
San Joaquin (11)		
Topsin M	0.03	0.02
Double Pruning	0.07	0.07
San Luis Obispo (8)		
Topsin M	0.02	0.02
Double Pruning	0.06	0.05
Lake (2)		
Topsin M	0.02	0.02
Double Pruning	0.06	0.05
Sonoma (3)		
Topsin M	0.01	0.01
Double Pruning	0.06	0.05

Table A.4 that the expected net benefits from adopting earliest do not always outweigh the additional expected cost of acting. As such, a grower's perception of the probability of an infection may lead them to prefer adopting in year 5 rather than year 3.

As noted above, if the discount rate were to change or different growers held different discount rates we might expect changes in  $\pi^0$ . When calculating  $\pi^0$  using a higher 5% discount rate, the threshold changed very slightly with most increasing. They all remained relatively close to the estimates shown in Table 8. Lastly, lowering the cost of the practice significantly reduces the infection probability threshold whereas the DCE does very little, comparatively. As such, we would expect investments in reducing the cost of preventative practices will likely have a greater impact on early adoption when growers are uncertain about the likelihood of an infection.

## 5. Conclusion

We find in all scenarios, a grower is better off adopting a preventative practice early than after the disease is apparent in the vineyard. In addition, our findings suggest a grower who adopts a preventative practice in year 3 will see the greatest net returns possible. Our results also illustrate the profitable lifespan of an infected vineyard can be increased by between 26% and 47% when adoption begins early. However, the length of time it takes for a practice to outperform, in terms of cumulative net returns, another practice or no action also affects perception of practice efficacy. Practices adopted in year 10 take the shortest time to pay for themselves relative to conventional pruning. In many scenarios the payoff is immediate. Practices adopted in year 3 take the longest to pay off. In some cases, it may take longer than if adopted in year 10. 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 also see the estimated infection probability threshold that divides growers between early adopters and adopters in year 10, when symptoms appear, are all below 0.17 and most are at or below 0.05 across the scenarios and counties. Evidence from a recent survey suggests widespread prevalence of trunk diseases among California vineyards (Hillis et al., 2015). If so, growers' perception of probability of infection are closer to one, implying that perception of the infection is not likely affecting the timing of adoption.

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. 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

Table A.1

Additional cumulative discounted net benefits (NB) per acre from adoption of a preventative practice (in thousands of 2013 dollars) with 50% and 75% disease control efficacy rates by county (crush district number) and practice scenario relative to adoption in year 10. Note, scenarios with bolded values have negative cumulative net benefits over a 25-year lifespan.

NB (1,000 2013\$) relative to year 10 s	25% DCE			75% DCE		
	Year 3	Year 5	No Action	Year 3	Year 5	No Action
Napa (4)						
Delayed Pruning	\$30.56	\$21.72	–\$16.16	\$65.44	\$57.53	–\$89.86
Topsin M	\$30.14	\$21.43	–\$15.47	\$65.02	\$57.24	–\$89.18
Double Pruning	\$27.75	\$19.78	–\$11.56	\$62.63	\$55.58	–\$85.26
Northern San Joaquin (11)						
Delayed Pruning	<b>\$8.50</b>	<b>\$6.04</b>	–\$4.49	\$18.20	\$16.00	–\$24.99
Topsin M	<b>\$7.98</b>	<b>\$5.68</b>	–\$3.64	\$17.68	\$15.64	–\$24.14
Double Pruning	<b>\$6.90</b>	<b>\$4.93</b>	–\$1.87	\$16.60	\$14.89	–\$22.36
Central Coast (8)						
Delayed Pruning	\$12.38	\$8.80	–\$6.55	\$26.51	\$23.31	–\$36.41
Topsin M	\$11.42	\$8.14	–\$4.98	\$25.55	\$22.65	–\$34.84
Double Pruning	\$10.19	\$7.28	–\$2.95	\$24.32	\$21.79	–\$32.82
Lake (2)						
Delayed Pruning	\$12.19	\$8.68	–\$6.45	\$26.11	\$22.97	–\$35.89
Topsin M	\$11.67	\$8.31	–\$5.91	\$25.58	\$22.61	–\$35.35
Double Pruning	\$10.56	\$7.54	–\$3.74	\$24.47	\$21.84	–\$33.17
Sonoma (3)						
Delayed Pruning	<b>\$15.40</b>	<b>\$10.95</b>	–\$8.14	\$32.97	\$28.99	–\$45.28
Topsin M	<b>\$14.96</b>	<b>\$10.64</b>	–\$7.43	\$32.53	\$28.68	–\$44.57
Double Pruning	<b>\$13.43</b>	<b>\$9.58</b>	–\$4.92	\$31.00	\$27.62	–\$42.06



Table A.2

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

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

Table A.3

Years until cumulative discounted net benefits of adopting a preventative practice exceeds those from an infected-untreated vineyard, by county (crush district number) and 25% DCE and 75% DCE practice scenario.

	25% DCE			75% DCE		
	Year 3	Year 5	Year 10	Year 3	Year 5	Year 10
Napa (District 4)						
Topsin M	3	1	0	1	0	0
Double Pruning	7	4	1	5	3	0
Northern San Joaquin (11)						
Topsin M	6	4	0	4	2	0
Double Pruning	8	6	2	7	5	0
Central Coast (District 8)						
Topsin M	6	4	0	5	3	0
Double Pruning	8	6	2	7	4	0
Lake (District 2)						
Topsin M	4	2	0	3	1	0
Double Pruning	7	5	1	6	4	0
Sonoma (District 3)						
Topsin M	4	2	0	3	1	0
Double Pruning	7	5	1	6	4	0

Table A.4

Infection probability threshold ( $\pi$ ) that divides population of growers between non-adopters and adopters by county (crush district number) for 25% and 75% DCE practice scenarios.

	25% DCE		75% DCE	
	Year 3	Year 5	Year 3	Year 5
Napa (4)				
Topsin M	0.01	0.01	0.01	0.01
Double Pruning	0.09	0.09	0.04	0.03
Northern San Joaquin (11)				
Topsin M	0.06	0.06	0.03	0.02
Double Pruning	0.17	0.16	0.08	0.06
Central Coast (8)				
Topsin M	0.06	0.05	0.03	0.02
Double Pruning	0.13	0.12	0.06	0.05
Lake (2)				
Topsin M	0.04	0.04	0.02	0.02
Double Pruning	0.13	0.13	0.06	0.05
Sonoma (3)				
Topsin M	0.03	0.03	0.01	0.01
Double Pruning	0.13	0.12	0.06	0.05

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. Furthermore, because most infections occur through pruning wounds once a vine is planted in the vineyard, investing in clean plant material is likely to provide minimal improvement. As an alternative, the industry could invest in technologies to increase DCE given improvements in DCE can offset the negative effects of waiting to adopt until symptoms appear. For example, a technology that predicts when pathogen spores are produced would help growers better time the preventative practices during the dormant season, thereby improving its effectiveness. Reducing the cost of preventative practices also increases early adoption, especially when growers are concerned about the time it takes for such a practice to payoff.

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## Appendix. Additional scenario results

See Tables A1–A4 is here.

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