Spatial Externalities and Vector-Borne Plant Diseases:
Pierce's Disease and the Blue-Green Sharpshooter in the Napa Valley

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ABSTRACT: Pierce's Disease (PD) is a bacterial disease that can kill grapevines over a span of one to three years. In this paper, we examine and model PD and vector control decisions made at the vineyard level in the Napa Valley in an effort to understand how the pest and disease affect individual growers, and to examine spatial externality issues and potential benefits from cooperation between adjacent vineyards. The model that we created adds to the literature by (a) treating grape vines as capital stocks that take time to reach bearing age and thus cannot be immediately replaced in the event of becoming diseased. We also (b) relax the assumption of an interior solution by examining the boundaries of parameter space for which winegrape growing is profitable and thus allowing growers to abandon land if it is not. We also explore (c) the effect of changing different policy parameters, such as PD control and vine replacement costs. Finally (d) we examine the potential benefits of cooperation between growers to manage vector populations, and determine that coordinated vector control could help riparian-adjacent growers to lessen grapevine losses and land abandonment, and thus to remain profitable in times of high PD pressure.

Key Words: Pierce's Disease, winegrapes, perennial crop modeling, agricultural pests and diseases, optimal control theory

Introduction

Pierce's Disease (PD), caused by a strain of the bacterium *Xylella fastidiosa* (*Xf*), was first reported in California vineyards in the 1880s. PD can kill grapevines over a span of one to three years by clogging the *xylem* and thus limiting water transport within the plant. Today, PD has been identified in grapevines in 28 California counties (California Department of Agriculture 2009).

In California, PD is spread mainly by sap-feeding insects called sharpshooters. The relevant species of sharpshooters and the nature of the problems they impose vary significantly among the major winegrape growing regions of California. In the Napa Valley, native Blue-Green Sharpshooters (*Graphocephala atropunctata*, BGSS) have vectored PD from riparian areas (near streams and rivers) into vineyards for many years. The problem there is regarded as chronic but manageable, with severity that varies from year to year. However, some growers have chosen to abandon otherwise exceedingly valuable land in areas where it is too difficult to control the disease (See Figure 1 for an aerial image of abandoned or partially-abandoned blocks).

In this paper, we examine and model PD and vector control decisions made at the vineyard level in the Napa Valley in an effort to understand how the pest and disease affect individual growers, and to examine spatial externality issues and potential benefits from cooperation between adjacent vineyards. The model that we created adds to the literature by (a) treating grape vines as capital stocks that take time to reach bearing age and thus cannot be immediately replaced in the event of becoming diseased. This builds directly upon the work of Brown (1997) and Brown, Lynch, and Zilberman (2002) who considered the same disease in the Napa Valley but did not consider the perennial nature of grapes. We also (b) relax the assumption of an interior solution by examining the boundaries of parameter space for which winegrape growing is profitable and thus allowing growers to abandon land if it is not. This issue is of particular interest because vineyard land in Napa County is some of the most expensive in the world (on average, between $225,000 and 300,000/acre), and thus abandonment represents a large opportunity cost (California Chapter of the American Society of Farm Managers and Rural Appraisers 2010).

We also explore (c) the effect of changing different policy parameters, such as PD control and vine replacement costs. These numerical explorations could offer insight to policymakers in times of PD stress, or in the event of the introduction of an exotic vector, such as the Glassy-Winged Sharpshooter, which has decimated vineyards in southern parts of the state. Finally (d) we examine the potential benefits of cooperation between growers to manage vector populations, and determine that coordinated vector control could help riparian-adjacent growers to lessen grapevine losses and land abandonment, and thus to remain profitable in times of high PD pressure.

Motivation

The main breeding habitat for BGSSs is in the riparian zone, although irrigated landscaped areas can also host breeding populations (Pierce's Disease/Riparian Habitat Workgroup 2000). While some BGSSs will remain in the riparian area throughout their lifecycle, some adult female sharpshooters leave in the spring and lay their eggs on lush new growth in surrounding vineyards. Upon hatching, nymphs go through several moltings before they become winged adults and can leave the plant on which they hatched. If a BGSS feeds on an infected plant, the bacteria can attach to its mouthparts and colonize there.[1] Prior to the adult stage, the BGSSs shed their mouthparts as part of each molting, but if they do become infected at the adult stage, they will remain so until their death, and can transmit PD with an efficiency of up to 90 percent upon any given feeding (Purcell and Finlay 1979).

The flight range for the BGSS is not far; most insects do not travel more than 800 feet from where they hatch. Nevertheless, the damage they inflict in riparian-adjacent vineyards can be substantial. In interviews we conducted with growers, many individuals stated that in vineyards near riparian corridors, PD caused major economic losses; some vineyard managers stated that it was the main reason for abandoning vineyard blocks in the most seriously affected locations (Grower A 2009; Grower B 2010).[2] Figure 1 in Appendix A shows aerial photos of vineyards with blocks of abandoned land.

In the Napa Valley, one of the main methods of contending with PD is to remove the riparian plants that harbor breeding populations of the BGSS. One vineyard manager interviewed stated that the removal of host plants can reduce PD-related vine loss by up to 90 percent (Grower C 2009). Others did not estimate such high effectiveness, but most stated that riparian revegetation could yield substantial economic gains, provided that work in the riparian area was not too difficult because of rocky or steep conditions. Even under good working conditions, costs associated with revegetation can be significant. The process of design, approval, and implementation of a riparian revegetation plan can take over a year to complete (Pierce's Disease/Riparian Habitat Workgroup 2000). To encourage survival of the new plantings, a drip irrigation system must be installed. Field interviewees gave estimates of between \$5 (Grower C 2009) and \$12 per foot of river

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[1] Plants that harbor PD are not limited to grapevines.

[2] Names are suppressed for confidentiality.

frontage (Grower A 2009) and beyond (Grower D 2010) for initial costs of revegetating a stretch of river.

While Napa County produced less than 4 percent of the total volume of the grapes crushed for wine in California in 2008, the winegrape crush in that year was valued at nearly $400 million, or over 20 percent of the total crush revenue in the state (California Department of Agriculture/National Agricultural Statistics Service 2009). Therefore, while it may be less threatening to the California wine grape industry than other vectors of PD, such as the newly-arrived invasive Glassy-Winged Sharpshooter that plays a role in the southern part of the state, growers and policymakers are very concerned about the damages and corresponding economic losses that the BGSS can cause.

Interviews

To get a better idea of the PD situation in Napa County, we interviewed seven vineyard managers during February and March of 2010, using a process called "participatory mapping." Aiming to glean insight into how PD costs and damages vary among properties, we asked respondents to sketch onto aerial images of their vineyard blocks where and how they manage PD and the associated costs. Each interviewee was presented with two images; one was for a block adjacent to a riparian area, while the other was as similar as possible in grape variety and clone, but relatively far away from the riparian zone. Figure 1 in Appendix A shows an example of an aerial image of vineyard blocks adjacent to the Napa River, onto which a vineyard manager has made notes regarding PD problems and associated management strategies such as aggressive replanting ("aggr. replant") or partial abandonment ("No replant").

A recurring theme in the interviews was the presence of spatial externalities. Specifically, vineyard managers worried if and how their neighbors were controlling for PD and how it might affect them. In what follows, we attempt to model those interactions and to examine how adjacent vineyard managers' decisions can affect each other.

Bioeconomic Model of Spatial Pest and Disease Externalities

Many published articles have used optimal control techniques to model the management of a pest or disease within an agricultural or wildlife setting. To our knowledge, though, none of these studies used optimal control to model pest and disease management for a perennial crop.

Several articles in particular have guided our thinking about the bioeconomic modeling of agricultural pests and diseases. Fenichel and Horan (2007) addressed bovine tuberculosis in deer populations, and showed that sex-based harvesting strategies can be an important tool in curbing disease prevalence. Bicknell, Wilen, and Howitt (1999) also examined bovine tuberculosis, but across different populations: as spread to cattle in New Zealand by Australian brushtailed possums. They showed the importance of the disease transmission rate in influencing the sensitivity of cattle farmers to rates of subsidy for trapping possums. Marsh, Huffaker, and Long (2000) addressed potato leafroll virus vectored by the green peach aphid, highlighting the influence of weather patterns and degree-day accumulation on the aphid population size and therefore its ability to vector the virus. Bhat and Huffaker (2007) used game theory to explore cooperation between adjacent landowners who face damages from beavers. They showed that the potential economic gains from cooperation are substantial, and are maximized in the scenario in which the landowners have the greatest flexibility in the extent of their cooperation.

Additional studies have considered the spatial spread of vectors, specifically for PD as vectored by the BGSS in the Napa Valley wine industry, but have not addressed the perennial nature of the crop. Brown, Lynch, and Zilberman (2002) emphasized disease transmission and source control for dealing with the problem.[3] The authors considered riparian plant removal, but focused mainly on barrier methods. This pest control method reduces the transmission of the disease from the riparian area into the vineyard by placing an obstruction between the source habitat and the vineyard. The authors assumed that vineyard managers would grow a barrier of Christmas trees, and that these trees could be sold. They modeled disease prevalence as a function of the effectiveness of the barrier in preventing the insects from moving into the vineyard, with the spread of the disease determined by the width and effectiveness of the barrier. The authors used these components to create a social decision problem with choice variables including (a) the width of the barrier; (b) input use; and (c) the extent of removal of source vegetation.

Brown (1997) modeled the decision of whether to remove riparian plants in greater detail. At the time of the study, riparian revegetation was not an option because of laws governing riparian areas, but Brown examined decisions regarding revegetation if it were legalized. She estimated that costs of removal and revegetation would have to be greater than $42 per foot to induce a profit-maximizing grower to choose not to undertake

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[3] The authors ignored pesticide use because, at the time of the article's publication, only one pesticide (Dimethoate 400) was permitted for riparian application and it required a special permit. This method of pest management is now illegal in Napa County. Imidacloprid, the current pesticide of choice for sharpshooters, was not examined.

revegetation. We build on this work by allowing explicitly for the perennial crop characteristics, which mean that loss of vines involves economic losses over multiple years. Considering the perennial nature of the crop may be especially important because it implies that grapevines should be treated as a capital stock.

A Basic Model

In this section we describe a bioeconomic model and the results from applying it to examine growers' decisions about PD control under a variety of scenarios defined in terms of the number of growers and the extent of their cooperation. We have created a basic model in which we use optimal control to define parameterized solutions for three scenarios: 1) a single isolated grower, 2) two growers, one of whom controls unilaterally, taking the neighbor's insect population (and therefore dispersal) as given, and 3) a social planner who maximizes the joint profit of multiple blocks with inter-block sharpshooter migration.

What follows is a basic model of a pest or disease that spreads over space and affects a perennial crop. We present this model in reference to PD in the Napa Valley, although it is applicable to other pests and diseases that affect perennials over multiple seasons. Let N_i represent the insect population on grower i's land. N_j represents the insect population on i's neighbors' properties, $N_1, N_2, \ldots, N_{i-1}, N_{i+1}, \ldots N_{\mathrm{M}}$. I_i represents the number of vines bought to replace those killed by disease and natural death, and Y_{i} is i's yield per vine that is healthy and has reached bearing age. A_i^{NB} and A_i^{B} represent the numbers of non-bearing and bearing vines, respectively. The cost functions for control and investment are expressed as $\mathrm{w}^{\mathrm{S}}(S_i)$ and $\mathrm{w}^{\mathrm{I}}(I_i)$, respectively. The price per ton of the grapes crushed is represented by p. S_i is the quantity of individual *i*'s control. Each grower chooses S_i and I_i to solve the following problem over a given time period, where ρ is the discount rate.

$$(1) \qquad \max_{I,S,N} \int_0^\infty \left[\mathrm{p} A_i^B \mathrm{Y} - \mathrm{w}^{\mathrm{S}}(S_i) - \mathrm{w}^{\mathrm{I}}(I_i) \right] e^{-\rho t} dt$$

This maximization problem is subject to several constraints in the form of differential equations. The equation of motion for the insect population is:

$$(2) \qquad \dot{N}_i = \left(\mathrm{R} N_i - \frac{\mathrm{R}}{\mathrm{K}} N_i^2 - \beta N_i S_i \right) + \sum_{j \neq i}^{I} \delta_{\mathrm{i,j}} N_j \,,$$

where R measures sharpshooter intrinsic growth rate, K is a measure of the carrying capacity of the insect population, β measures the effectiveness of the control, and $\delta_{\mathrm{i,j}}$, ($\delta_{\mathrm{i,j}} \leq 0$) is the entry from the *i*th row and the *j*th column of the MxM dispersal matrix, where M is the total number of growers. The change in non-bearing and bearing vinestocks, A_i^{NB} and A_i^B, also are defined by differential equations. Each stock has a separate equation; since grapevines take between three and five years to reach bearing age, it is not possible for growers to buy replacement vines that will bear immediately.[4] The vines are modeled as capital stocks and the pest causes a loss of capital, a departure from annual crop models in which the pest causes a loss of yield in current production ().[5]

$$(3) \qquad \dot{A}_i^{NB} = I_i - \mu A_i^{NB} - \mathrm{d}^{\mathrm{NB}} A_i^{NB} N_i$$

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[4] Pierce's Disease kills the entire grapevine, including the root system. Therefore, grafting is not an option for vine replacement.

[5] Note that the control can also be structured to reduce insect carrying capacity, which would more accurately reflect the case of riparian revegetation. This is easily accomplished by allowing the control to change the relationship of R and K. Results are available in which we conducted analyses in this fashion. However, the two sets of results are not substantively different, and the model above allows greater generality since it could apply to either pesticide application or riparian revegetation.

$$(4) \qquad \dot{A}_i^B = \mu A_i^{NB} - \mathrm{d}^{\mathrm{B}} A_i^B N_i - \eta A_i^B$$

The parameter d^j, $j=NB, B$, measures the damage to the non-bearing or bearing stock, respectively, that is caused by each insect. The percentage of vines that mature from non-bearing to bearing each year is represented by μ, and η represents the percentage of vines that die of natural causes each year. Additionally, the total number of vines that grower *i* can have is constrained by the total amount of land in a given block, $\bar{\mathrm{A}}_i$, which can be greater than the sum of all planted acres if the grower chooses to leave some land fallow. In (5) a_i converts vines to acres (its units are acres/vine).

$$(5) \qquad \bar{\mathrm{A}}_i \geq \mathrm{a}_i (A_i^{NB} + A_i^B)$$

Social Planner Case

The social planner aims to maximize the sum of profits across all landowners on the riparian strip, *i=1,…,M*. Because the land constraint does not vary over time, we write the problem as a Lagrangian instead of a Hamiltonian (Kamien and Schwartz 1991). The Lagrangian in the social planner case, assuming quadratic cost functions, can be written as:

$$(6) \qquad L = \sum_{i=1}^{M} \left\{ \begin{array}{l} \mathrm{p} A_i^B \mathrm{Y} - \mathrm{w}_0^S S_i - \mathrm{w}_1^S S_i^2 - \mathrm{w}_0^I I_i - \mathrm{w}_1^I I_i^2 + \lambda_i^{NB} \left(I_i - \mu A_i^{NB} - \mathrm{d}^{\mathrm{NB}} A^{NB} N_i \right) + \\ \lambda_i^B \left(\mu A_i^{NB} - \mathrm{d}^{\mathrm{B}} A^B N_i - \eta A_i^B \right) + \lambda_i^{\bar{A}} \left(\mathrm{a} \left(A_i^{NB} + A_i^B \right) - \bar{A} \right) + \\ \psi_i \left(\mathrm{R} N_i - \dfrac{\mathrm{R}}{\mathrm{K}} N_i^2 - \beta N_i S_i + \sum_{j=1}^{I} \delta_{\mathrm{i,j}} N_j \right) \end{array} \right\}.$$

Assuming an interior solution, the optimal control first-order conditions on the control variables, *S* and *I*, are given in Equations (7) and (8).[6] At the optimum, the marginal cost of vine replacement is equal to the shadow value of a non-bearing vine, and the marginal cost of an additional unit of control is equal to the value of the marginal damage, which is positive since ψ_i <0.

$$(7) \qquad \frac{\partial L}{\partial I_i} = -\mathrm{w}_1^I I_i - \mathrm{w}_0^I + \lambda_i^{NB} \equiv 0 \text{, or, } \mathrm{w}_1^I I_i + \mathrm{w}_0^I = \lambda_i^{NB}$$

$$(8) \qquad \frac{\partial L}{\partial S_i} = -\mathrm{w}_1^S S_i - \mathrm{w}_0^S - \psi_i \beta N_i \equiv 0, \text{ or, } \mathrm{w}_1^S S_i + \mathrm{w}_0^S = -\psi_i \beta N_i .$$

Taking derivatives of the Lagrangian with respect to the shadow values gives us back the equations of motion. To allow for land abandonment in the land constraint, we use Kuhn-Tucker conditions:

$$(9) \qquad \frac{\partial L}{\partial \lambda_i^{\bar{A}}} \le 0.$$

If (9) is strictly negative, land is abandoned, and $\lambda_i^{\bar{A}} = 0$. If, instead, $\lambda_i^{\bar{A}}$ > 0, then (9) must equal zero, with all land planted in vines (Kamien and Schwartz 1991). Note that the derivative of (5) also implies that when absent abandonment,

$$(10) \qquad \dot{A}_i^B = -\dot{A}_i^{NB},$$

meaning that the change in the stock of bearing vines is equal to the negative of the change in the non-bearing vines, Alternatively, with some abandonment,

$$(11) \qquad \dot{A}_i^{Aband} = -\mathrm{a}\left(\dot{A}_i^{NB} + \dot{A}_i^B\right),$$

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[6] Chiang (1992) showed that additional state-space equations must be satisfied to check the robustness of the solution when there are constraints on the state variables that do not include the control variable.

meaning that any change in one of the bearing, nonbearing, or abandoned acreage stocks is equal to the negative of the combined change in acreage of the others.

The full system of equations is rounded out by the costate conditions, some of which we have omitted here to conserve space.

(12) $$-\frac{\partial L}{\partial N_i} \equiv \dot{\psi}_i - \rho \psi_i \Rightarrow$$

$$\dot{\psi}_i - \rho \psi_i \equiv -\left(-\mathrm{d}^{NB} \lambda_i^{NB} A_i^{NB} - \mathrm{d}^{B} \lambda_i^{B} A_i^{B} + \psi_i \left(\mathrm{R} - 2\frac{\mathrm{R}}{\mathrm{K}} N_i - \beta S_i \right) + \sum_{j=1}^{N} \psi_j \delta_{ji} \right), \text{or,}$$

$$\dot{\psi}_i \equiv \mathrm{d}^{NB} \lambda_i^{NB} A_i^{NB} + \mathrm{d}^{B} \lambda_i^{B} A_i^{B} - \psi_i \left(\mathrm{R} - 2\frac{\mathrm{R}}{\mathrm{K}} N_i - \beta S_i - \rho \right) - \sum_{j=1}^{N} \psi_j \delta_{ji}.$$

The insect population costate equation, (12), is interpreted such that that any change in the value of damage caused by sharpshooters is a function of the shadow value of vines lost to PD and the current shadow value of insects adjusted for the marginal productivity of the insect and discounting, as well as dispersal; growers take into account the insects that leave their properties (δ_{ii}).

For one isolated grower, the sole difference in the model is that the dispersal term drops out. Thus (12) becomes

(12a) $$\dot{\psi}_i \equiv \mathrm{d}^{NB} \lambda_i^{NB} A_i^{NB} + \mathrm{d}^{B} \lambda_i^{B} A_i^{B} - \psi_i \left(\mathrm{R} - 2\frac{\mathrm{R}}{\mathrm{K}} N_i - \beta S_i - \rho \right),$$

and thus the isolated grower takes into account only the damage resulting from the insects on his own property. Only his own control decisions affect the number of insects in his vineyard.

Non-Cooperative Case

The ways in which the different growers interact can vary, and a scenario in which a social planner benevolently organizes them is extremely rare. Following Janmaat (2005), we explore an alternative situation in which each grower maximizes his own profit without regard for the effect on his neighbors. The optimization results differ from those of the social planner in Equation (12).

Solving for N_i and comparing the outcomes from the social planner and non-cooperative cases in the steady state shows that insect populations will be greater under the noncooperative regime compared with the social planner regime; in Equation (13) N_i^{SP} represents the number of BGSSs under the social planner regime, and N_i^{NC} represents the number under the noncooperative regime. Because $\delta_{ii} \leq 0$ and $\psi_i < 0$, it follows that $N_i^{SP} \leq N_i^{NC}$ by a difference of $\frac{2\mathrm{R}\delta_{ii}}{\mathrm{K}}$, ceteris paribus, or more explicitly:

(13) $$N_i^{SP} = \frac{2\mathrm{R}\left(\dot{\psi}_i + \psi_i\left(\mathrm{R} - \rho - \beta S_i\right) - \mathrm{d}^{NB}\lambda_i^{NB}A_i^{NB} - \mathrm{d}^{B}\lambda_i^{B}A_i^{B}\right)}{\mathrm{K}\psi_i} \leq$$

$$\frac{2\mathrm{R}\left(\dot{\psi}_i + \psi_i\left(\mathrm{R} - \rho + \delta_{ii} - \beta S_i\right) - \mathrm{d}^{NB}\lambda_i^{NB}A_i^{NB} - \mathrm{d}^{B}\lambda_i^{B}A_i^{B}\right)}{\mathrm{K}\psi_i} = N_i^{NC}.$$

Numerical Results

Because of both the number of constraints and their nonlinear nature, an analytical solution is not feasible, even for a one-grower case in which dispersal is disallowed for the purposes of simplification. Instead, we now present numerical analyses for examples of one-grower and multiple-grower or (multiple-block) cases at their steady states.[7] The parameterization of these models is described in Appendix B. While the choices of parameters were informed by interviews with growers and relevant literature, as well as discussions with scientists, exact parameter estimates were not readily available in all cases and therefore the results presented should be thought of as numerical examples rather than empirical case studies.[8]

One-Grower Case

If one vineyard represents the entire universe of our interest, dispersal of insects between different landowners need not be considered. In this case, the grower maximizes individual profit subject to the same constraints described above, with the exception of (2), the insect population equation, which drops its $+\sum_{j=1}^{I}\delta_{\mathrm{i,j}}N_j$ term.

To determine the importance of the different parameters in the one-grower case, we conducted comparative statics using the steady-state solutions of the model over a range of scenarios. To begin, we looked at the single-grower case in which one isolated grape grower maximizes profit subject to damage from sharpshooters, but experiences neither in- nor out-migration of the insects. While this scenario is unlikely in the real world, it is not impossible given that some vineyards in Napa may be surrounded by land without BGSS host plants. For example, this could be the case if a given grower was surrounded by neighbors that had all revegetated their riparian land. We examined the

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[7] Further analysis could include studying the dynamic path of these solutions to determine whether that additional level of complexity could lend understanding to the issue. However, in preliminary dynamic analysis, adding an allowance for adjustments over time had little effect.

one-grower optimal outcomes over a range of several parameters: control cost, vine replacement cost, crush price, and vine maturity rate.

As expected, as we increased the price of control, the optimal quantity of control fell, and to compensate, the number of vines replaced increased. However, over the feasible range of control prices, no land was abandoned, because it was still relatively cheap to replace vines. With less and less control, the number of sharpshooters increased toward the carrying capacity of the block. With more vines needing to be replaced, the shadow value of land fell.

Changing the price of vine replacement had more dramatic effects on the results. As we increased the price of vine replacement, control increased to reduce the required number of vines being replaced. Once vine replacement became too expensive, at roughly $150/vine (less with a higher discount rate), both control and vine replacement declined rapidly with additional increases in vine prices, the sharpshooter population increased, and the grower began to abandon land. For a graphical representation of this case, see Figure 1.

Comparative statics for the crush price of winegrapes are also of interest. When we decreased the crush price below $1,200/ton, some land was left fallow, which is consistent with statements of some growers in interviews who reported that low crush prices in recent years had led them to abandon certain blocks (or parts of blocks). The entire block (10 acres) was utilized when the crush price reached around $1,200/ton.[9] As the crush price increased, so did the shadow value of marginal land, which was zero until the crush price rose above $1,200/ton. Additionally, as the crush price increased, more control was utilized and more vines were replaced, and as a result the number of

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[9] No land was planted when the crush price was set at zero.

sharpshooters on the property fell. When we decreased the crush price and the cost of vine replacement simultaneously, land abandonment occurred sooner than if either element were varied on its own.

We also varied, μ, the parameter that measures vine maturation speed, in order to get a better idea of the importance of treating vines as capital stocks that take time to bear fruit, in contrast to annual crops. While this is not a parameter that policymakers have control over, it can help us to understand the effects of treating grapevines as annuals rather than capital stocks that take several years to mature. As the speed at which vines mature was increased, so too did the shadow value of land, the optimal sharpshooter population, the number of bearing vines, the amount of vines replaced, and the quantity of control. Varying μ alone did not influence land abandonment, although slower-maturing vines in combination with a low crush price or high vine replacement cost caused more land abandonment than would occur otherwise. Thus, treating vines as an annual rather than a perennial crop can yield estimates of land value that are overinflated, and predict less use of control and more vine replacement at the optimum. Mature vines that take longer to replace are more valuable, and thus more worth protecting, *ceteris paribus*.[10]

The discount rate also played an important role in determining the values of parameters for which land was abandoned. The default discount rate used here is 3 percent per annum. When we increased the discount rate it caused a substantial drop in the values of vine replacement cost and crush price for which land abandonment began, and the value of crush price for which land was abandoned increased. At a 7 percent

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[10] Note that if vine maturation speed were to change, it is likely that other parameters, such as crush price, would also change, perhaps in dramatic ways.

discount rate, land abandonment began when the vine replacement cost was $65/vine, roughly 55 percent less than the critical value of $145 using a 3 percent discount rate. Likewise, using a 7 percent discount rate, land abandonment began at a crush price of $1,800/ton, a 33 percent increase over the critical crush price of $1,350 that applied for a discount rate of 3 percent.

Two (Noncooperative) Growers, Unilateral Control

In this case, we examined the optimal actions of a single grower with one neighbor who does not control. We allowed the neighbor's insect population to vary and examined the changes in optimal actions of the grower in question in response to changes in the given insect populations on the neighbor's land. Additionally, while we fixed the sharpshooter carrying capacity on Grower 1's land at 80, it is possible that a neighbor could have a higher carrying capacity, so we allowed N_j to reach 120 at its maximum. We (somewhat arbitrarily) assumed that 30 percent of the each grower's population migrates into their neighbor's vineyard.

As we increased the number of insects on the neighbor's property, control on Grower 1's land became less effective, since it was negated in part by the influx of sharpshooters from neighboring land. As a result, control fell as the number of insects on a neighbor's property increased. As control dropped off and more insects migrated in, the number of vines replaced increased. Grower 1's own population of insects increased toward carrying capacity, and the shadow value of Grower 1's land fell. However, Grower 1 did not abandon any land.

When we changed other parameters along with the neighboring sharpshooter population, the land abandonment results changed. While large numbers of in-migrating insects alone did not cause a grower to abandon land, Figure 3 shows that, in combination with high vine replacement costs, large numbers of neighboring sharpshooters caused the grower to abandon land at lower vine replacement costs than otherwise (approximately $150/vine, depending on the influx of insects).

Social Planner with Two Blocks

Next we assumed that a social planner manages two vineyard blocks, to maximize their combined profit, with grapes grown on Block 1 fetching half the price of grapes grown on Block 2. We allowed the sharpshooters to migrate between the two properties in the same fashion as in the unilateral control case; the difference here is that the planner determines the control strategy in both blocks, so neither population is taken as given. This is a frequent scenario in Napa, where individual growers often own and manage blocks in various locations across the county and beyond, so control over multiple blocks is common. However, it is also common for different growers to own adjacent blocks of land, so it is interesting to examine this case in order to determine the possible gains from cooperation between these growers.

As in the one-grower case, as we increased the price of control, both blocks utilized less of it and instead substituted more vine replacement. Over the range of control costs we examined, the social planner always devoted more control to the high-priced block (Block 2) than the low-priced block (Block 1) since the opportunity costs of foregone crop were higher in Block 2 than in Block 1. As we increased control costs, the sharpshooter populations in both blocks increased, but the planner did not abandon land in either block.

As we increased the price of vine replacement, the planner increased control and decreased vine replacements. In Block 1, at $170/vine, the marginal shadow value of land fell to zero, and the social planner began to abandon land. Up until this point, the increase in control on both blocks led to lower sharpshooter populations, with slightly fewer sharpshooters in Block 2 than Block 1. After that point, however, control in Block 1 fell and vine replacement dropped drastically. Because control dropped off in Block 1, the sharpshooter population in that block increased. While the planner did not abandon land in Block 2 at the same price point as in Block 1, Block 2 began to see increased in-migration of insects because of the reduction in control in Block 1 and consequently any control used in Block 2 was less effective. However, the planner did not abandon land in Block 2 over the relevant parameter space. Note that the price per vine at which land began to be abandoned is $170, roughly 12 percent higher in the social planner case than in the two-grower, unilateral control case, supporting the hypothesis that cooperative control strategies could reduce abandonment. Figure 4 shows control and sharpshooter population as functions of vine replacement cost for both blocks.

We also experimented with the effects of changing the discount rate for the social planner case. When we increased the discount rate from 3 to 7 percent per annum, the planner abandoned land in Block 1 at a lower cost of vine replacement, roughly $65/vine, or approximately a 40 percent decrease. The planner also abandoned land in Block 2, although this did not occur until the vine replacement cost reached approximately $140/vine.

These comparative statics are helpful in showing which parameters have the most impact as well as in forming testable hypotheses. For example, we expect land adjacent to sharpshooter habitat to be less valuable but land to be worth more if it is next to a neighbor who does a good job of controlling for sharpshooters. Not surprisingly, we expect land to be more valuable if it is planted with vines that either mature faster or fetch a higher crush price.

We also expect high vine replacement cost and/or low crush price to lead growers to abandon land across a range of scenarios, and a high discount rate will exacerbate land abandonment in those cases. Perhaps most notably, as long as vines can be replaced relatively cheaply, land abandonment is fairly insensitive to the cost of control as well as numbers of in-migrating insects. These could be important pieces of information for policymakers looking to support grapegrowers during periods of high pressure from PD; those looking to provide relief to grapegrowers should look to mechanisms that reduce the price of vine replacement, or compel growers to cooperate regarding their control schemes.

Conclusions

We constructed this model specifically to examine the Napa Valley/BGSS-vectored PD issue. In the southern parts of the state, however, the PD problem is quite different and potentially more threatening to the wine industry there. One potentially valuable extension of our model might focus on the issue of PD as it affects the winegrape industry in southern California. Major concerns about PD grew after a devastating outbreak in the Temecula Valley (in southern California) in the late 1990s, spread by the newly-arrived, non-native Glassy-Winged Sharpshooter (GWSS), which has much greater capacity to spread PD than the BGSS because it can fly much longer distances (up to a half mile at a time) and can feed lower on the grape cane. The GWSS does not depend on riparian or irrigated plants but instead tends to overwinter in citrus groves, and has the ability to feed on a wide range of plants (Hill 2010). The GWSS thrives in citrus orchards, which are widespread in southern California. While PD problems caused by the GWSS in southern California are larger and more difficult to model in some ways, the spatial externality problem is similar and this could be a useful extension of the model described here.

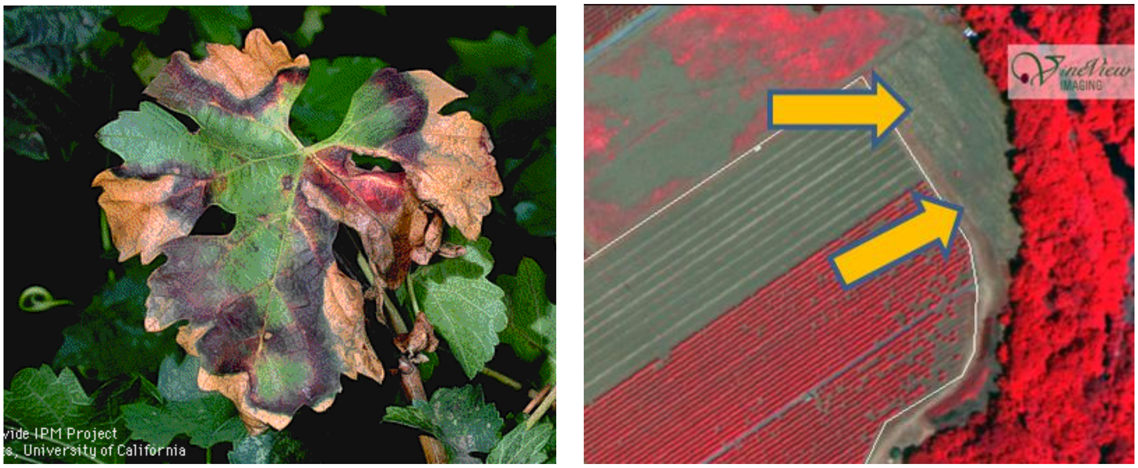
In this paper, we have used spatially-explicit modeling techniques to gain a better understanding of how grapegrowers' actions indirectly cause them to interact with each other through their sharpshooter populations. We carefully take account of the biological characteristics of the insects as well as the perennial nature of the crop being examined, which both represent differences from other attempts to examine this disease in particular and other pest and disease problems in agriculture. This work shows how these characteristics, in concert, can cause growers to abandon land that is affected by the disease, shedding light on a little understood issue in the Napa Valley. Specifically, we used a weak inequality constraint to model the constraint on total available land, which allowed us to explore land abandonment. While the introduction of this seemingly simple tweak to the classic optimal control model complicated the process of obtaining solutions, it also showed the importance of doing so in this case as it helps to show why land is being abandoned in the Napa Valley, an area that contains by far the most valuable vineyard land in the California (California Chapter of the American Society of Farm Managers and Rural Appraisers 2010).

The results of the numerical analyses can be used to guide policymakers in aiding grape growers in times of high PD pressure. These results suggest that if heterogeneous growers can work together to coordinate BGSS control, they will be better off in that they will experience less damage from PD and will abandon less land. In times of high PD pressure, policymakers could create pest control districts in which growers (and residential property owners alike) would be required to treat for BGSS, which could help curb losses. Additionally, by varying the vine maturation rate, we found that it is important to consider the perennial, capital stock nature of the grapevines. When we allowed the vines in the model to mature immediately, as in the annual crop case, the vine replacement costs for which land was abandoned were much higher, as was the estimate of the shadow value of land. Our numerical analysis also indicates that some parameters can be much more useful than others in determining the viability of a vineyard. The price of vine replacement, in particular, stands out as an important parameter in determining whether vineyards are profitable. Thus, subsidies on winegrape plantings would be much more efficient than subsidizing controls or other inputs in assisting grapegrowers in times of high-PD stress.

Appendix A: Tables and Figures

Figure 1: Images of Pierce's Disease

1a. Diseased Vine and example of land abandonment in the Napa Valley



1b. Participatory Mapping Example

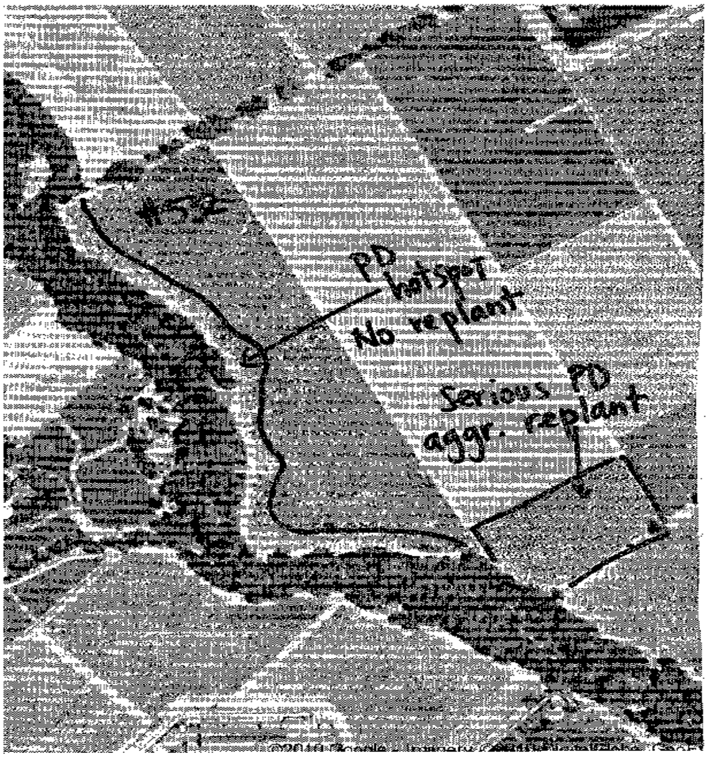


Figure 2: Selected comparative statics for vine replacement cost, one grower case

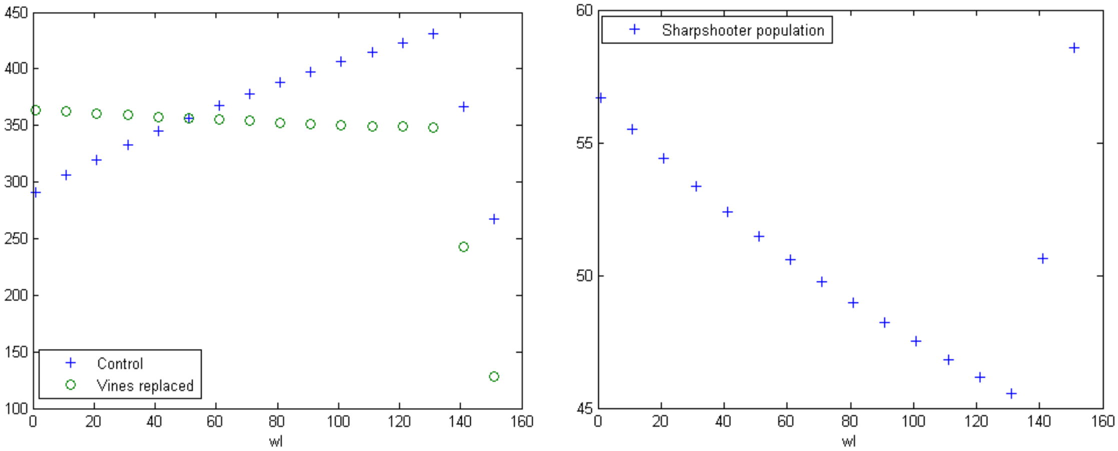


Figure 3: Abandoned land as a function of vine replacement cost and neighbor's sharpshooter population

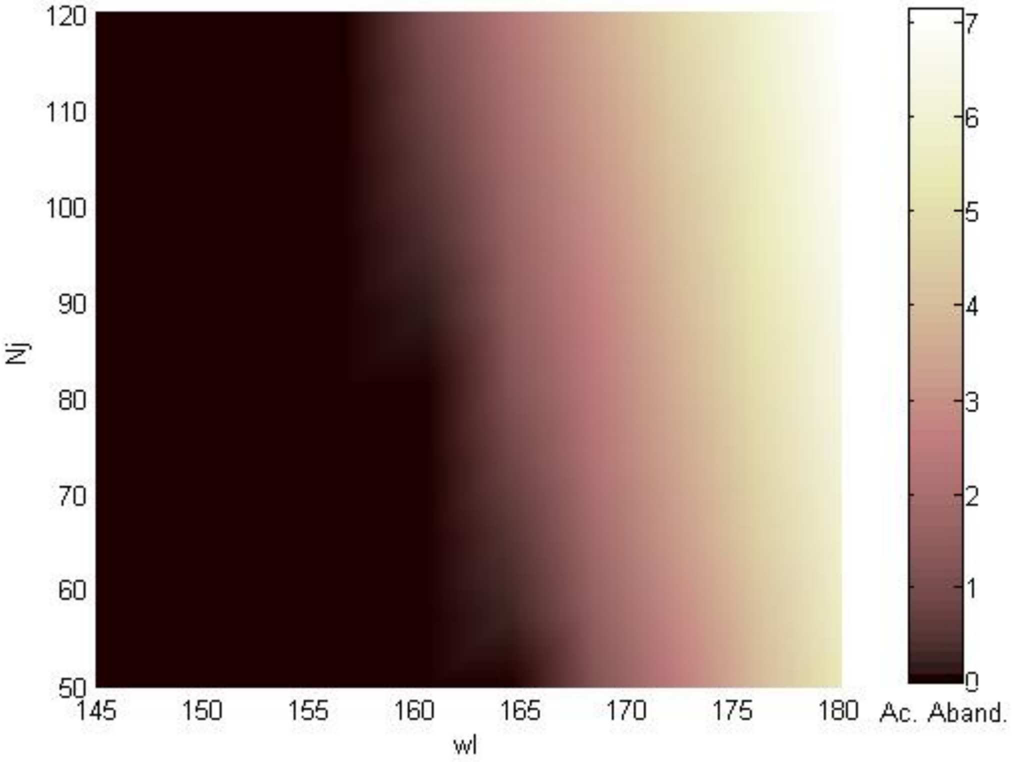
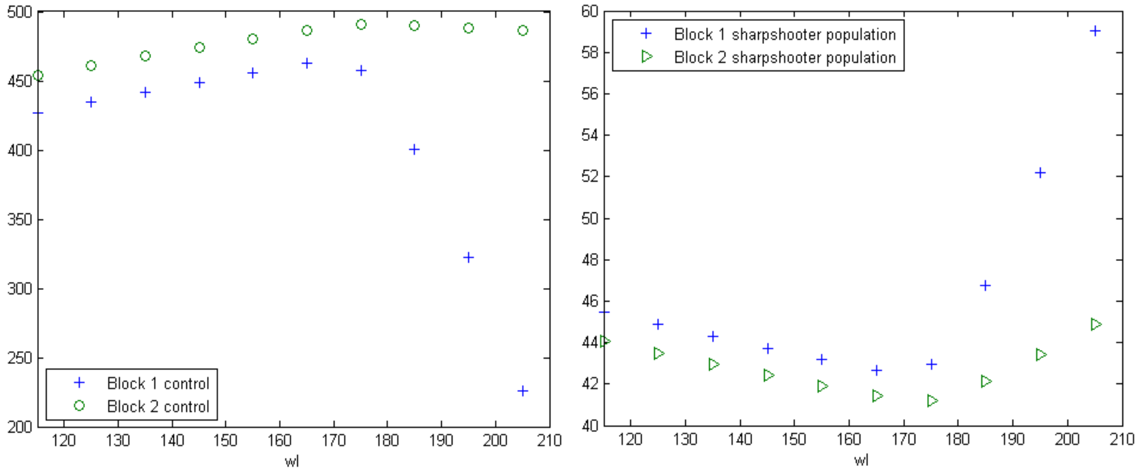


Figure 4: Selected comparative statics for vine replacement cost, social planner case



Appendix B: Model Parameterization

Table 1 summarizes the parameters that we used in the model. The values assigned were chosen by reviewing the relevant literature as well as consulting experts. As a result, we have a reasonable amount of confidence in the estimates used, but in some cases they should be viewed as best guesses rather than statements of fact. The numerical analysis was conducted using the TOMLAB package in MATLAB using both the *knitro* and *snopt* solvers.

The cost of control is measured by the parameter w^{S}, with the total control cost being quadratic in controls, $\mathrm{w}^{\mathrm{S}}S+0.01\mathrm{w}^{\mathrm{S}}S^{2}$. In the base case, we used $\mathrm{w}^{\mathrm{S}} = 6$, which was chosen by speaking with grape growers during interviews about riparian revegetation as well as alternative control strategies. The cost of vine replacement is structured similarly, with the total cost equal to $w^{I}\mathrm{I}+0.01w^{I}\mathrm{I}^{2}$. The base cost of $11/vine was taken from both interviews with farmers and the Cabernet Sauvignon Vine Loss Calculator for Napa (Klonsky and Livingston 2009).

For several of the biological parameters we utilized, exact measures were not available. To estimate these parameters, we discussed them with Barry Hill, the CDFA entomologist and then conducted sensitivity analyses, many of which are described in the body of the paper. These include the kill rate, β, and the damage parameter, d, which can be interpreted as the probability that any one insect will cause disease in a given vine. At this time we have assumed for simplicity that the rate of damage to non-bearing and bearing stocks is the same, although the model is written so that these could be different rates. The sharpshooters' natural growth rate, R, and measure of carrying capacity, K, were determined in the same fashion. Note that the carrying capacity is reached at $\dot{N} = 0 = \dot{N} = \mathrm{R}N\left(1 - \frac{N}{K}\right)$, so $\bar{N} = \mathrm{K} = 80$. The dispersal matrix is based on the same methods. We have assumed at this point that no one grower represents a sink (more insects enter than exit her property) or a source (more insects exit than enter her property); instead in our model the properties are fully integrated and insects migrate in both directions.

We utilized quantity and acreage (to calculate yields) and crush prices from (rounded) historical averages for Cabernet Sauvignon in the Napa Valley, using the 2009 Crush and Acreage Reports (California Department of Agriculture/National Agricultural Statistics Service 2009), and the number of vines per acre was taken from (Klonsky and Livingston 2009). The block acreage ($\bar{\mathrm{A}}$) was in the range of block sizes that growers in Napa County reported. The rate of vine maturity, μ, is based on vines that reach maturity at 5 years, which was typical for growers interviewed. In order to avoid explicitly adding time-lags into an already continuously dynamic model, we assume that since vines can be replaced each year, 0.2 of all of these non-bearing (immature) vines become bearing (mature) each year. The non-PD death rate is based on interviews with farmers.

Table 1: Base Level Parameter Values and Explanations

Parameter	Explanation	Given value
w^S	Unit cost of control ($/unit)	6
w^I	Unit cost of investment ($/vine)	11
d^{NB}	Damage per insect per vine for non-bearing vines	0.0001
d^B	Damage per insect per vine for bearing vines	0.0001
R	Natural growth rate of sharpshooter population	2
K	Sharpshooter carrying capacity	80
β	Proportion of insects killed per unit of control	0.001*R
Y	Yield/vine (tons)	0.00382
a	Acres/vine (acres)	1/1555
$\bar{A}$	Scale unit at which the problem is solved (acres)	10
ρ	Annual discount rate	0.03
μ	Annual rate of vine maturity from non-bearing to bearing	0.2
η	Annual non-PD death rate	0.02
p	Crush price in the one-grower model ($/ton)	4000
p_1	Crush price for Block 1 in two grower model ($/ton)	3500
p_2	Crush price for Block 2 in two grower model ($/ton)	7000
δ_{ij}	Dispersal between properties; symmetric.	0.3

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