The Economics of Controlling Insect-Transmitted Plant Diseases

by

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Introduction

There is growing literature on the economics of alternative mechanisms of controlling pests in agriculture. Researchers have developed models to analyze pest control decisions under a variety of strategies (see survey by Carlson and Wetzstein). Some of these strategies include chemical use, monitoring and disrupting the life cycle of the pest through trapping and sterile insect release, using beneficial insects and bio-control, altering cultural practices, and developing resistant varieties. Pest problems are transmitted across locations (e.g. insect flight, carriage of weed seeds by wind, and pathogens transmitted by vectors) and can be controlled by impeding the transmission process. This paper develops a framework for analyzing a spatially dependent pest problem emanating from a source and spreading via a vector, and investigates the use of transmission and/or source control in combating a pest or disease problem. In particular, we design optimal barriers to slow the spread of a pest or disease problem under alternative assumptions about the feasibility and cost of reduction of the pest population at the source. We apply simulations of the model to the problem of controlling Pierce's disease (PD) in California wine grapes.

The analysis relies and expands on the literature originated by Von Thunen (Dovring) that suggests that transportation cost tends to explain allocation of land among agricultural activities. His model predicts that production intensities and land values will increase in locations closer to urban centers. Several authors (see survey by Miranowski and Cochran) have investigated land allocation over space under alternative assumptions about production technologies and externalities. They found that environmental quality considerations tend to reduce production intensities near cities or bodies of water when agricultural production generates pollution, and they introduced incentives to modify production accordingly. The literature also considers situations where productivity is affected by spatial movement of resources. Chakravorty, Hochman and Zilberman analyzed controlling the loss of productivity in irrigated agriculture due to conveyance losses. They derived optimal investment in improved conveyance and showed that optimal water use and output declines with distance from the source, while the price of the input (water) increases. In this paper we model the spatial transmission of pest damage and design an optimal control strategy in terms of barrier design and pest reduction at the source. In our case, the barrier consists of land diverted from the main crop (e.g., grapes) to an alternative crop (e.g., hops) that produces less income but significantly slows the movement of the pest. The next section provides an introduction to the spatial transmission problem and a theoretical model. It is followed by an empirical analysis of transmission control use by itself, or use of transmission and/or source control when source control is decided by a grower or by a social maximizer.

Background

Many plant diseases caused by viruses or bacteria are transmitted to plants by an insect vector.[1] Strains of the bacterium *Xylella fastidiosa*, which are transmitted by sharpshooter leafhoppers, cause several significant plant disease problems.[2] The presence of sharpshooters and *Xylella fastidiosa* in Florida plums was such an acute problem that the plum industry no longer exists in that state. Similarly, almonds can no longer be produced in parts of California because of the almond leaf scorch problem that occurred throughout some of the state's almond-producing counties (Purcell(b), 1999). Several species of sharpshooters, which regularly occur in citrus groves of Brazil, have caused the rapid spread of a strain of

Xylella fastidiosa, causing citrus variegated chlorosis (CVC) to spread to citrus-growing regions of Brazil. CVC is now a major concern of Brazil's $1.4 billion a year citrus industry. Replacement of dying oleanders planted along California's highways, as a result of oleander leaf scorch, is estimated to cost at least a minimum of $330 million (Lynch, et al., 1999).

One particularly important disease caused by *Xylella fastidiosa* is Pierce's Disease (PD) in wine grapes. Recent PD outbreaks in California's Napa Valley are estimated to have cost vineyard owners $33 million in 1997 (Associated Press, 1998). In the last century PD infected 35,000 acres of vineyards in southern California destroying the Anaheim grape industry. Although average statewide losses in most years are small, individual vineyards can sustain large losses. The presence of PD in the southeastern United States from Florida to Texas makes it almost impossible to grow European-type (*Vinifera*) grapes for wine in these states.

PD requires two components to spread. One is the bacterium *Xylella fastidiosa*; the second is a vector of transmission, the xylem-feeding sharpshooter leafhoppers (*Cicadellinae),* which transfer the bacteria from an infected host plant to other plants. Once infected, yield decreases, and often the vine will die. The leafhoppers breed and overwinter in riparian vegetation, ornamentals and/or pastures, picking up the *Xylella* bacteria from host plants. The insects then migrate in the spring to feed on succulent vegetation, such as grape vines, infecting the vines as they spread. An infectious blue-green sharpshooter has more than a 90 percent chance of transmitting the bacteria (Varela, 1996).

Disease control has been elusive. Because PD is an insect-transmitted disease, growers can attempt to reduce or eliminate the insect to reduce bacteria transmission. However, insecticides have limited effectiveness on PD in vineyards where the sharpshooters enter each spring from riverbank vegetation. Applying insecticide to the riparian area where the insects are concentrated might control PD spread, but only one insecticide (Dimethoate 400) is currently available through a special local need permit, and only two applications per year are permitted due to wildlife and water quality concerns. In addition, there is little evidence that insecticides are cost-effective (Purcell, 1993). Crops planted between the source area and the economically important agricultural crop can act as a barrier to transmission to slow or prevent the sharpshooter migration, but this strategy requires taking land out of grape-production. Some experimentation is currently being conducted on the effectiveness of barrier crops to control PD. Removal of the bacterial and sharpshooter host plants at the source might reduce incidences of the disease. Replacing host vegetation with non-host varieties could prevent the bacterium's survival as well as the sharpshooter's overwintering, and thus, the transmission of the disease into the fields. This paper models controlling transmission of the disease through the use of several different barrier crops. Then the optimal barrier profit function is used to determine a grower's or a social maximizer's decision on using source control. Since the grower does not control removal decisions, we look at the conditions under which the U.S. Fish and Wildlife Service might permit clearing of the host vegetation from the source area.

Theoretical Framework

An agricultural region is located near a riparian area containing vegetation that is a source of disease-carrying insects. The size of the source population is a function of the number of plant species that host the insects. One source control strategy consists of removal of host plants from the area. The host plants also provide environmental amenities (wildlife habitat, water quality protection), and their removal is costly in terms of the loss of these amenities.

The removal of a percentage of the host plants will decrease the pest population and impose a cost on society. Let N_0 denote the size of the pest population, which will decrease with the loss of the source host area or source control activities. If no source control is conducted, i.e. no host plants are removed, the pest population size is $\overline{N}_0$. The social cost of source control (i.e., plant removal cost and environmental cost from reduction of riparian area) is $R(N_0)$. If no source control is conducted, $R(\overline{N}_0)=0$. It is reasonable to assume that the cost increases at an increasing rate as the source population is reduced, i.e., $\partial R / \partial N_0 < 0, \partial^2 R / \partial N_0^2 < 0$. The cost reaches an upper bound at $R(N_0 = 0)$ when the entire pest population at the source is eliminated. A regional environmental agency (in our case the U. S. Fish and Wildlife Service) controls the extent to which the habitat in the source will be modified, and farmers take N_0 as given. We will first analyze the farmer's choice and then consider the social optimization.

Model of Transmission Control

To control an insect-transmitted disease, a grower must examine the economic tradeoffs between the different transmission control mechanisms and crop production at the edge of the field. A theoretical model is developed to compare the tradeoffs in erecting or planting a barrier. Transmission control involves placing a barrier between the source area and the production area. The spatial aspects of the problem are described in Figure 1. The insects live in source vegetation at location *0*. If a barrier is in place, the insects must travel through the barrier, which has width *a* (in feet), to reach a row of the main crop which is planted perpendicular to the source. The length of each row of the main crop is measured in feet from *a* to *A*. The location of each plant can be designated by x, the distance from the source.

A plant closer to the source is more likely to have damage from the disease, since the per-plant density of vectors is highest on these plants. The probability of contracting the transmitted disease is a function of the number of pests and the distance from the source. The vector population, N, at a distance of x from the source can be represented by $N(x)$. The damage, D, inflicted by this vector population is $D(N(x))$.

The percentage of vectors that migrate from the source into the crop row when no barrier exists is represented by the pest movement function. The population at location x is $N(x) = N_0 m$, where m is the percentage of vectors that migrate from the source into the crop at location x. The movement depends on the distance and the properties of the barrier. The barrier width is a, and we assume that there are I different types of barriers. Let i be the barrier crop indicator, $i = 1, I$. The relative effectiveness of 1-foot of barrier type i, β_i, is the percentage of vectors blocked by 1 foot of barrier, with $0 \leq \beta_i \leq 1$. Thus, the movement function with barrier i is $m(x,\beta_i,a)$. When there is no barrier at all, the movement function is $m(x,0,0)$. Movement of the insects declines with distance $(\partial m / \partial x < 0)$, declines with the size of the barrier at a decreasing rate $(\partial m / \partial \alpha < 0, \partial^2 m / \partial \alpha^2 > 0)$ and declines with barrier effectiveness $\partial m / \partial \beta_i < 0$. Following Lichtenberg and Zilberman, the damage function is $D(N_0 m(x,\beta_i,a))$ with $\dfrac{\partial D}{\partial m} > 0$ and $\dfrac{\partial^2 D}{\partial m^2} < 0$. Lower m corresponds to more pest abatement. Each grower chooses the optimal barrier type and width to maximize profits, trading off acreage of the main crop for increased yields on the remaining acreage, along with profits from the sale of the barrier crop.

Growers determine the optimal strategy by first computing the maximum profit, π_i, for each barrier type, and then selecting the barrier type with the highest profit. For each barrier type the grower chooses optimal levels of inputs, w, for production of the main crop, optimal levels of inputs, u, for production of the barrier crop, and the optimal barrier width, a. We assume that all of the crops are sold in competitive markets, so the price of the main crop, P_g, and the price of the barrier crop, P_i, are exogenous to the model. The grower's optimization problem for barrier type i is:

$$\begin{aligned} \pi_i(N_0) = \max_{w,u,a} &\int_0^a \left[P_i b_i(u,x) - c_i(u,x)\right] dx - FC_i(a) \\ &+ \int_a^A \left[P_g f(w,x)(1 - D(N_0 m(x,\beta_i,a))) - c_g(w,x)\right] dx \end{aligned} \quad . \tag{1}$$

The plant production function of the main crop, $f(w, x)$, has the characteristics $\frac{\partial f}{\partial w} > 0$, and $\frac{\partial^2 f}{\partial w^2} < 0$. The per plant production function for barrier crop i, is $b_i(u, x)$, with properties of $\frac{\partial b_i}{\partial u} > 0$ and $\frac{\partial^2 b_i}{\partial u^2} < 0$. The variable cost of production for the main crop, $c_g(w, x)$, and for the barrier crop i, $c_i(u, x)$, are assumed to be a convex function of inputs with $\frac{\partial^2 c_g}{\partial w^2} \geq 0$ and $\frac{\partial^2 c_i}{\partial u^2} \geq 0$. Let $FC_i(a)$ denote the fixed annual costs of installing barrier i of width a with $\frac{dFC_i}{da} > 0$. There are no economies or diseconomies of scale, thus $\frac{\partial^2 FC_i}{\partial a^2} = 0$.

The first order conditions for this problem are:

$$\int_a^A \left[P_g \frac{\partial f(w,x)}{\partial w}(1- D(N_0 m(x,\beta_i,a)))\right] dx = \int_a^A \frac{\partial c_g(w,x)}{\partial w}\, dx \tag{2}$$

$$\int_0^a P_i \frac{\partial b_i(u,x)}{\partial u}\, dx = \int_0^a \frac{\partial c_i(u,x)}{\partial u}\, dx \tag{3}$$

$$\begin{aligned} & P_i b_i(u,a) - c_i(u,a) - \frac{\partial FC_i(a)}{\partial a} = \\ & P_g f(w,a)(1- D(m(a,\beta_i)N_0)) - c_g(w,a)\,. \\ & + \int_a^A \left[P_g f(w,x) \frac{\partial D}{\partial m} \frac{\partial m(x,\beta_i,a)N_0}{\partial a} \right] dx \end{aligned} \tag{4}$$

The first order conditions, with respect to *w* (equation 2) and *u* (equation 3), convey the usual profit maximization requirement that marginal revenue equals marginal cost for production of the main and the barrier crop. For the main crop, we find that a grower will purchase inputs at each point *x*, given the level of production at this location, and the decrease in yield due to disease (which is impacted by the width of the barrier), as long as the marginal cost of these inputs are below the extra revenue earned at this point. So the individual farmer makes multiple choices for the field depending on the distance from the source area and the impact of the disease at that location. For the barrier crop (equation 3), the farmer will purchase inputs to grow the barrier, given that the marginal revenue earned from this crop at location *x* is at least as large as the marginal cost of the inputs. Equation (4) is the first order condition for the choice of the barrier width. The grower will add another foot of the barrier crop if the marginal benefit equals the marginal loss of another foot of the main crop, plus the marginal benefit from a reduction in yield loss on the remaining plants of the main crop. As the barrier blocks the transmission of the disease, yields in the remaining area of the main crop will increase. While the grower does not want to take out the main crop, if the increase in yields in the rest of the field outweighs the loss from this removal, the grower will increase the width of the barrier.

The optimal levels of the barrier width and inputs are for barrier type *i* denoted by $a_i^*(\gamma)$, $w_i^*(\gamma)$, $u_i^*(\gamma)$, where $\gamma = (P_g, P_i, \beta_i, N_0, A)$. Using the implicit function theorem, we solve the comparative statics with respect to the crop price, the price of the barrier crop, the effectiveness of the barrier crop, the initial size of the pest population, and the length of the grape row (Appendix A, Brown).

Table 1 shows how the barrier width changes as parameters change in the model. The optimal width of the barrier increases as the price of the barrier crop increases relative to the value of the main crop, which did not change. The barrier width increases with an increase in the price of the main crop, conditional on the intensive effect being greater than the extensive effect. The intensive effect is the effect on yield for the whole row of the main crop. The extensive effect is the effect on crop yield at the margin where the main crop row meets the barrier. In other words, when the main crop price increases, if the increased protection afforded the crop row by increasing the width of the barrier is greater (less) than the loss at the margin of replacing some main crop area with the barrier crop, the width of the barrier will increase (decrease).

The width of barrier *i* increases with the effectiveness of barrier *i* conditional on the intensive effect being greater than the extensive effect. As each unit of barrier *i* is more effective (β increases), barrier *i* gives more "bang for the buck." If the decrease in damage in the crop row that an extra unit of the more effective barrier *i* provides is greater (less) than the loss at the margin of replacing some of the main crop with the crop of barrier *i*, the width will increase (decrease). As the initial level of vectors increases, a grower will increase the barrier width to obtain better protection against the vector population. The optimal barrier width declines as the length of the crop row decreases. Because the main crop is a higher value crop relative to the barrier crop, the grower will grow more of it in the shorter row and less of the barrier crop. In addition, fewer plants need protection in a shorter row, so the grower can use a narrower barrier.

After obtaining $\pi_i(N_0)$ for every *i*, the optimal barrier type is selected by comparing profits across the various alternatives so that $\pi_i^*(N_0) \geq \pi_j(N_0)$ for $i^* \neq j$. The grower's profit, given N_0, is determined by $\pi^*(N_0) = \pi_i^*(N_0)$. The optimal level of source control is determined by choosing the optimal N_0 (or the number of source plants to remove), which is determined by maximizing profit minus the cost of source control:

$$(6) \qquad \max_{N_0} \pi^*(N_0) - R(N_0)$$

The assumptions about the production and cost functions of the farmer suggest that they will be concave and well-behaved especially if one barrier type is optimal for all N_0. As we will see, less is known about the shape or impact of source control on society's costs, $R(N_0)$. If the objective function is concave, the optimal solution is an interior solution which occurs at $0 < N_0 < \overline{N}_0$, where the marginal grower's yield loss associated with a higher N_0 is equal to the marginal environmental gain associated with a higher N_0.

On the other hand, we could have a corner solution where no source control occurs or where all the source host plants are removed. If the marginal environmental benefit from maintaining the source area (riparian zone) is very low relative to the gain from source reduction in terms of a lower pest population, we will see $N_0 = 0$, or complete source removal. Alternatively, if the environmental benefits of the riparian system are very high, or at $N_0 = \overline{N}_0$, we find that $\left|\frac{\delta R}{\delta N_0}\right| > \left|\frac{\delta \pi^*}{\delta N_0}\right|$, and it will be optimal to have no source reduction.

Empirical Analysis of Transmission Control

We use numerical simulations based on the current problems with PD of grapes in the Napa Valley of California to examine the economics of a spatially dependent insect-transmitted disease and the relationship between the intensive and extensive margin. Currently, the zoning regulations and the jurisdiction of the U.S. Fish and Wildlife Service over the riparian area, the PD source area for Napa Valley vineyards, have prevented growers from controlling the disease at the source. Grape growers' only option is transmission control, and they have proposed installing barriers of hops or Christmas trees to prevent transmission. Hops and Christmas trees have different time frames for costs and returns, and so need to be made comparable to each other and to the annual return from an established vineyard. To make these comparisons, annual equivalent incomes (AEI) are calculated for both hops and Christmas trees using an interest rate of 6 percent.[3] Hops require one year to establish before full production and are considered a 10-year investment. Christmas trees are harvested in years 8 through 10.

One acre of grape vines with no PD infection returned a profit of $4,096 per year in 1996 with a yield of 6 tons per acre at a grape price of $1,300 per ton (MKF). With PD infection following the spatial pattern indicated in Figure 2, and with no barrier, per acre profits drop to $1,261. A grower can increase profits by removing grapevines from the area nearest the riparian habitat since these vines cost more to produce when infected with PD than revenues generated. Profits increase to $1,853 when 214 feet of vines are removed.

Christmas trees have an AEI of $1,202 per acre; hops have an AEI of $757 per acre. While Christmas trees earn more, the relative effectiveness between trees and hops as a barrier is important. We simulate a range of barrier effectiveness parameters. Hops could be more effective because they grow faster than trees. Consequently, hops would provide protection several years earlier than trees. However, hops may not leaf out early enough in the spring to block sharpshooter movement during this critical time, thus lowering their effectiveness relative to Christmas trees.

Purcell (1974) has estimated the relationship between the percentage of symptomatic grape vines and distance from the source area. For Cabernet Sauvignon grapes, the regression equation is: y = 93.9 - 95.6 log x, where x is the distance from the river measured in 10 vine space units.[4] Infected vines sustain yield losses that are assumed to follow this spatial pattern as given in Figure 2. This adjusted regression equation is used to simulate yield loss that occurs when a grower does nothing to prevent transmission. Thus the damage function, including the possibility of transmission control, is: $D = e^{-a\beta_i}(93.9 - 95.6\log\frac{x}{80})$, where a is the barrier width, β_i is a parameter containing the factors that affect barrier effectiveness, and x is distance from the river measured in feet.

Table 2 provides a comparison of the two barrier types for a range of effectiveness and barrier widths. Growers with PD infections in their vineyards lose income relative to growers with no PD. Removing and not replanting infected vines near the riparian area can increase profits from PD-infected vineyards. Christmas trees perform better as a barrier than hops when the barrier width and effectiveness parameters are the same. As barrier effectiveness increases, barrier width declines. With a barrier effectiveness parameter of 0.5, profit levels increase to those of vineyards with no PD infection.[5] The last two rows of Table 2 show the barrier width and effectiveness parameter combinations needed for hops and Christmas trees to return the same profit.

As a barrier's effectiveness increases, the barrier's optimal width decreases. Under the assumption that damage follows the spatial pattern in Figure 2, PD is always worse closest to the source. The comparative static results indicate that the barrier width will increase with an increase in barrier effectiveness if the intensive effect is greater than the extensive effect. The simulation results indicate that the intensive effect is less than the extensive effect. In other words, the impact of increased effectiveness of the barrier on grape yield at the margin is greater than the effect on yield in the remaining row of grapes.

A key element that determines the economic viability of the barrier is the ratio of the barrier crop price to the grape price. For grape prices between $1,300 per ton and $1,269 per ton, the barrier width does not change. When the price of grapes falls to $1,268 per ton, the barrier width increases to 71 feet, and profits are $3,607 per acre. The comparative static results indicate that as the price of grapes falls the barrier width will also fall, if the intensive effect is greater than the extensive effect. The simulations show that, as the price of grapes falls, the barrier width increases. Therefore, the effect on yield for the remaining row of grape vines must be less than the gain at the margin from taking out grapes to increase the barrier width by planting more Christmas trees. When the price of grapes falls to $817 per ton the barrier crop dominates grapes, i.e. a grower should plant only Christmas trees. Similarly, as the price of Christmas trees goes up, the barrier width continues to increase. When the price of Christmas trees is $28.52 per tree (AEI = $2.05) the grower can maximize profits at $4,098 by planting the whole acre to trees. This agrees with the comparative static result that the optimal barrier width increases with the price of the barrier crop.

Empirical Analysis of Growers Choosing Source and/or Transmission Control

Unfortunately, little information about the impact of source alteration on yields is available at this time. For example, we do not know if the yield loss decreases at a decreasing, constant, or increasing rate as host plants are removed. The cost of removing the vegetation, if replacement is not required, is approximately $86.40 per acre for a riparian strip 6 ft. wide. For a typical vineyard, it takes two employees working eight hours a day at $8.00 per hour four days to clear vegetation from an area 6 feet wide and 400 feet long (Henderson). Using this estimate, the cost is $1.28 to remove vegetation from a 6-feet-by-1-foot area. A 1-acre field made up of nine rows of grapes has 6.75 feet between each row. Assuming that one row space (6.75 feet) of host vegetation must be cleared on either side of a row, an area 67.5 feet long and 6 feet wide would need to be cleared at a total cost of $86.40. Given this cost, if the growers get permission to remove the existing vegetation, they will remove it all, and by removing the source of the insect vector, end the PD problem. If growers are limited to removing less than 90 percent of the host vegetation, it is always more profitable to use only a transmission control method. At removal rates of 90 percent or more, it is more profitable to combine source and transmission control rather than transmission control alone (Figure 3). If total removal is permitted, growers will choose to remove all the source vegetation.

Given that grape growers clearly benefit from 100 percent source plant removal, we consider under what conditions society benefits from the removal of riparian area vegetation. The Fish and Wildlife Service or similar agency maximizes society's welfare, which is the total benefits from improved water quality and wildlife habitat provided by the riparian vegetation minus the losses from PD and the cost of host plant removal.

As our theoretical model indicates, the plants in the riparian area should be removed only if their benefits to society are less than the value of the lost yield and the cost of removal. Since the 1970s, more than 400 papers have been published describing various aspects of the nutrient-riparian vegetation-water interface with the rate of publication about 30 to 35 papers per year (Correll). Yet we found no publication calculating the economic value of the riparian area's existence to society. We can, however, use the losses from PD and the cost of removal as the vegetation's minimum value required to protect it from removal.

Simulations were run using various grape prices to determine the value levels of the riparian vegetation at which society benefits from removal of the riparian area. We assume that all the host vegetation in a 100-ft. long by 6-ft. wide area along the field and stream is removed. By removing the plant hosts of the sharpshooter and *X. fastidiosa*, the yield damage associated with PD decreases to zero. With our base price equal to $1,300 per ton, we find that unless the riparian area provides benefits greater than $4,072 for this 100-feet-long area, society would be better off removing the sharpshooter habitat and permitting the farmers to grow PD-free. If grape prices increase to $2,500 per ton, we find that the riparian vegetation should remain in place only if it provides a value to society of $13,015 per area. In Figure 4, we present a range of grape prices and the accompanying riparian values. Using other methods to determine society's willingness to accept the losses incurred by grape growers would be helpful in maintaining these riparian areas and help guide policy decisions. More research needs to be done to understand the complex relationship between source area vegetation removal and its effect on PD incidence and yield loss in adjacent vineyards to make better recommendations about source control.

Policy Implications & Conclusions

Two possible biological control methods for controlling PD in wine grapes were examined when the disease was transmitted by insects from host plants in an adjacent source area using a spatial model. When yield loss due to the disease follows a spatial pattern similar to that given in Figure 2, growers can increase their profits by planting a barrier next to the source area to block insect movement into the vineyard.

In terms of PD, this paper shows the need for information on the effectiveness of both source and transmission control of diseases caused by *Xylella fastidiosa* to optimize a farmer’s welfare. In addition, society’s welfare is impacted by the removal of plants from the riparian area. Removal of source vegetation that hosts the disease is a potential, but controversial, method for PD control. When the source is riparian habitat, it is strictly regulated, and any alteration may adversely impact fish and wildlife populations as well as water quality. If the attempt to reduce yield loss from PD to zero requires removal of 100 percent of the vegetation, the cost incurred by wildlife or on water quality could be high. We see it is always in the grower’s best interest to remove all of the offending riparian vegetation; profits are highest with 100 percent removal. However, it may not be in society’s best interest for this vegetation to be eliminated. We think of it as an amount society would have to pay the grower not to remove too many plants if the grower has the right to do so. Policymakers may also decide on barrier use over plant removal through cost share programs and/or by lowering the profit from plant removal with regulation limiting the number of plants that can be removed, or by requiring replanting.

The cost of source alteration could be higher than estimated here if society imposes costs other than those incurred in actual plant removal. If growers need to pay for permits to remove vegetation, for inspection of the riverbank area before and after modification, or for research on the effects of altering the riparian habitat, profits from this PD control method will be lower. If the host vegetation is replaced with alternate plants, perhaps beneficial aspects of the riparian habitat can be maintained, although at a higher cost to growers. Society may need to intervene to achieve the most beneficial riparian habitat. One option is to forbid removal of any riparian vegetation. This is the current situation, but does not account for the damage done to grower's vineyards. Another option is regulation that requires replacing the plants removed with other non-host plants. Society could subsidize all or part of the grower's replanting efforts to encourage PD control and beneficial riparian habitat. Regulation may be the best solution if the shadow price of habitat is high. If the shadow price is low, increasing the cost to growers of plant removal, along with cost share plans for replanting, may be an effective solution. Understanding how the source area impacts yield loss due to PD is important for finding the appropriate policy tool to address the situation.

In a more general sense, the paper demonstrates that, when one cannot use a chemical or biological control to solve a pest problem, a grower may have to resort to a more radical approach such as altering the landscape or changing the crops planted. Landscape alteration that requires removal of plants that provide environmental amenities can impose high costs on society, which provides an indicator of the economic value of an environmentally friendly chemical or biological control that could solve pest or disease problems.

The use of both transmission and source control poses research challenges for ecologists and biologists. Effective barriers need to be identified that impede the pest and disease movement as well as provide profits to the landowners. Strategies to modify riparian zones to eliminate or reduce pest populations with minimal impact on wildlife and water quality must also be determined. Research on these issues is currently on-going.

The analysis indicates that modifying the source of the problem is most appropriate when it protects a high-value crop unique to a special location such as grapes in Napa Valley. When pests cannot be controlled by traditional means, production of higher value crops can only be accomplished with new and economically efficient pest control mechanisms. Production of other impacted crops would simply cease or move to a new location.

The analysis also explores the importance of understanding the movements of pests over space. The effectiveness of barriers depends on the mobility of the vectors. Increased mobility of the vector will require larger investment in barriers and may reduce the effectiveness of pest control using barriers.

This analysis considers only the production activities of a representative farmer. Yet, the land along the source area could be divided among several producers. One farmer’s actions will affect the neighbor farm’s profits. In addition, producers who live up-field from a source-bordering neighbor may also have yield impacts dependent on their down-field neighbor’s behavior. In these cases, regional cooperation may be needed to solve these types of spatially-transmitted pest problems, we plan to explore this in future work.

Table 1. Comparative Static Results

Parameter	Direction of Change in Barrier Width
Price of Barrier Crop *i*	+
Price of Main Crop	+ (if intensive>extensive)
Effectiveness of Barrier *i*	+ (if intensive>extensive)
Initial Sharpshooter Population	+
Length of Row for Main Crop	+

Table 2. Simulation of Hops and Trees as Barriers

	Total Profits* (per acre per year)	Barrier Width (feet)	Barrier Effectiveness Parameter
No PD	$4,096**	0	---
No barrier	$1,261	0	---
No barrier with vine removal	$1,853	214	---
Hops barrier	$2,814	202	0.005
Trees barrier	$2,930	218	0.005
Hops barrier	$3,743	67	0.05
Trees barrier	$3,781	70	0.05
Hops barrier	$3,888	41	0.1
Trees barrier	$3,911	42	0.1
Hops barrier	$3,999	20	0.25
Trees barrier	$4,010	21	0.25
Hops barrier	$4,043	12	0.5
Trees barrier	$4,049	12	0.5
Hops barrier	$3,911	37	0.1155
Trees barrier	$3,911	42	0.1

* With a grape price of $1,300 per ton.
** Yield is 6 tons per acre.

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[1] Some examples are: mosaic virus of cucumbers, corn, peppers and tomatoes transmitted by aphids; squash mosaic virus transmitted by beetles; tobacco ringspot transmitted by nematodes; squash leaf curl transmitted by whiteflies; spotted wilt of tomatoes transmitted by thrips; curly top of beets and other plants transmitted by beet leafhoppers; and aster yellows of carrots transmitted by leafhoppers.

[2] These include almond leaf scorch, phony peach disease, plum leaf scald, citrus variegated chlorosis, alfalfa dwarf, oleander leaf scorch, and PD on grapes.

[3] To calculate the annual equivalent income (AEI) the present net worth (PNW) of each crop is calculated. The PNW is then multiplied by the land expectation value (LEV) multiplying factor. The LEV is the net discounted present value of an infinite series of production periods. The LEV is then multiplied by the interest rate to obtain the AEI. (Standiford)

[4] One vine space unit is equal to 8 feet. Thus, $x = 1$ stands for 1-10 vine spaces or 80 feet, $x = 2$ for 11-20 vine spaces or 160 feet, etc.

[5] In Napa Valley in California, experiments with barrier plants are currently being conducted and some information about barrier effectiveness should be available in the coming years.

Figure 1.

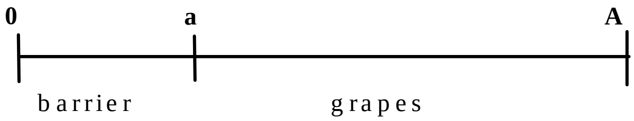

Figure 2. Yield Loss as a Function of Distance

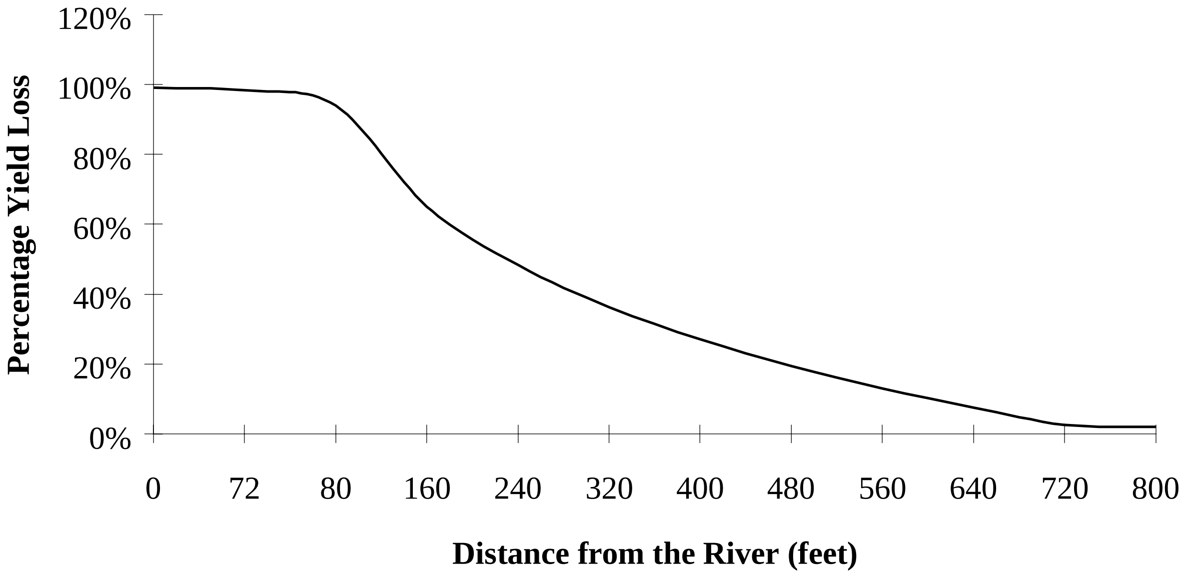

Figure 3. Comparison of Barrier Only vs. Barrier Plus Plant Removal

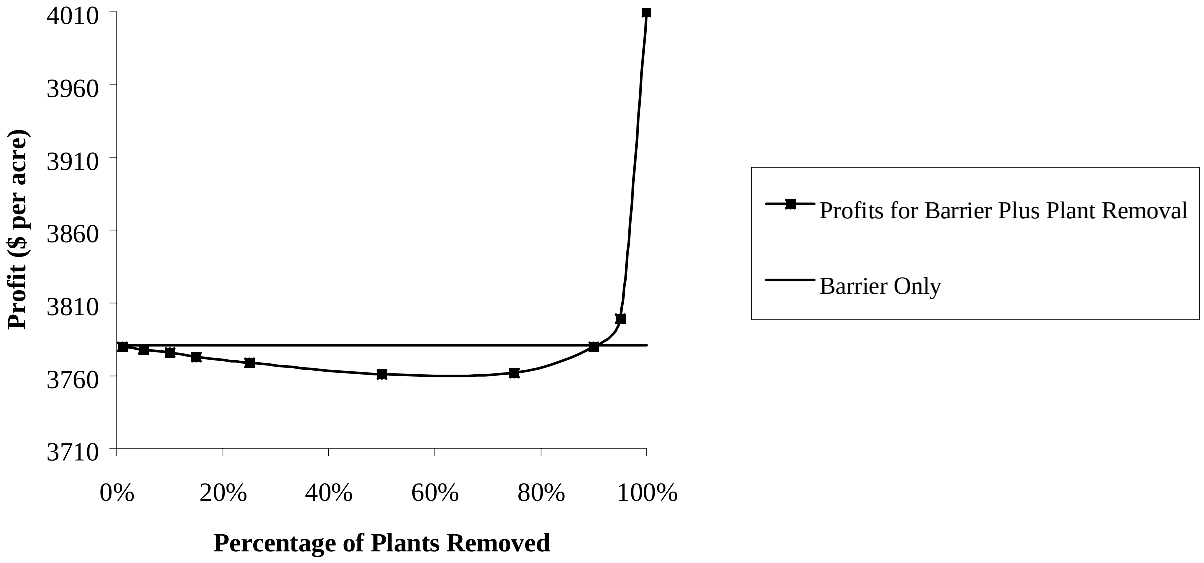

Figure 4. Value of Preserving Riparian Area Under Changing Grape Prices