Management of HLB Infected Citrus Groves in Florida: Some Empirical Results

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Introduction

Huanglongbing (HLB) is a bacterial disease that affects all varieties of citrus. It is commonly referred to as citrus greening. HLB was first discovered in Florida in 2005 and is now found in all counties where commercial citrus is produced (Manjunath et al. 2008). It is spread by a small leaf-feeding insect, the Asian citrus psyllid (ACP). The ACP was first found in June 1998 in Delray Beach, and it is noted for its short range maneuverability and long range drift by wind, implying simultaneous within and across spatiotemporal host plant spread. HLB acts to disrupt the phloem of the tree thereby limiting its ability to uptake nutrients. Initially this leads to yellowing of leaves, promotion of premature fruit drop, and production of small, misshapen fruit that contain bitter juice with no economic value. As the disease spreads through the tree, the amount of usable fruit produced diminishes until eventually the tree is of no economic value (Brlansky et al. 2011). At the present time, there are no known measures that effectively combat the disease. The standard protocol to control HLB includes controlling psyllid populations, routinely inspecting the trees for visual symptoms of the disease, and immediately eradicating trees where HLB symptoms have been found (Bové, 2006).

Just a few months after the discovery of HLB in Florida, the citrus canker eradication program was terminated following the sweeping spread of canker over most southern Florida groves by a series of hurricanes that visited the citrus belt in 2004 and 2005. Later in 2005, an interdisciplinary team of USDA HLB experts declared HLB endemic to Florida, with no chances of eradication (Gottwald and Dixon, 2006). So far, it is even more troubling to note that neither the citrus industry nor the state or USDA has put in place a clear cut and decisive procedure for control of HLB, unlike in the case of the aborted citrus canker control program. As a result, Florida citrus growers have evolved over the years three different management prescriptions to deal with the menace of HLB. In this paper, we develop a model to simulate the economic consequences of the three strategies given certain grove characteristics such as average grove age, rate of spread of the disease, initial disease incidence at first detection of HLB, and average grove yield. Results indicates that which strategy is superior to the other(s) depends on the age of trees at first detection and the initial rate of disease incidence at first detection.

Strategies of Control

At this time, there are three distinct strategies being employed to deal with greening. Strategy 1, referred to as “do nothing”, allows the disease to spread and takes no measures to slow its spread including controlling psyllid populations or mitigating HLB’s impact on tree health. Strategy 1 has no effect on per acre costs as management tactics are not modified. Per acre revenues, however, are gradually affected as the disease spreads and the number of healthy fruit that can be harvested and utilized gradually declines. At some point, per acre revenues will not cover per acre grove maintenance costs and at that point, the grove is no longer economically viable. The disease spreads faster in younger groves, so younger groves cease to be economically viable at a faster rate compared to an older grove with the same initial level of infection.

Strategy 2 follows the standard plant pathology disease control model and is the only internationally accepted control strategy for HLB (Aubert, 1990). Under Strategy 2, an aggressive psyllid control program is also put into place to suppress psyllid populations. Next, between four and twelve inspections are conducted annually to identify symptomatic trees. Once found, symptomatic trees are immediately eradicated (Brlansky et al. 2008). The logic behind Strategy 2 is that by eradicating symptomatic trees, the level of inoculum in a particular citrus grove gradually will be reduced. Eventually the incidence of the disease will be reduced to a point where it can be economically tolerated. Muraro (2010) has estimated that in Florida, Strategy 2 increased production costs by about $450 per acre. There are five problems associated with Strategy 2. First, plant pathologists have yet to characterize the key parameters that would significantly define the timeline by which to control HLB through eradication of symptomatic trees. These parameters include a controllable base level of HLB infection, the number of years it would take to achieve that base level, and the probability that young tree resets will survive to productive maturity. Second, the latency period of the disease implies that not all diseased trees will be removed in a timely manner, and these asymptomatic trees will serve as a reservoir of the disease inoculum. Third, if a grove is already at a high level of known infection and given that more trees are infected but not yet symptomatic, it may not be possible to effectively reduce inoculum levels in a particular grove without eradicating the entire grove. The probability of this outcome is related to the age of the grove and the level of infection when the first positive tree is found. Fourth, eradication or suppression of the disease to a tolerable level in one grove may not be possible if neighboring growers are not adequately suppressing the disease in their groves. Neighboring groves will serve as sources of the inoculum, and the disease may be continually re-introduced into the groves of the grower following Strategy 2. Fifth, relying on visual detection of HLB-infected trees by scouting is estimated to be about 50%–60% effective in finding all the symptomatic trees in a single survey. One other factor that also impacts the effectiveness of this strategy is the neighbor’s HLB management behavior. If psyllid control or tree removal is not coordinated with neighbors of a grove, inoculum builds up in the local vicinity.

Strategy 3 is an approach first developed in southwest Florida and is, in part, a response to the Achilles heel of Strategy 2, namely if Strategy 2 is initiated too late, the entire grove may be eradicated before the disease can be suppressed. While an initial high rate of disease incidence is one possible motivation to adopt Strategy 3, it is also possible that under some conditions, Strategy 3 may yield a higher return than Strategy 2 even though Strategy 2 could successfully reduce HLB inoculums to a manageable base level. Strategy 3 proposes to treat the symptoms of HLB through foliar application of micro and macro nutrients. The tree’s defense response to an HLB infection is to produce compounds that block phloem vessels of the tree’s vascular system. This resulting damage to the root system inhibits the ability of the tree to uptake nutrients from the ground. In the foliar feeding method, a portion of the nutritional needs of the tree is applied through foliar sprays including both macro and micro nutrients (Spann et al. 2010). Formulation of the enhanced nutritional program depends on the program, but generally the active ingredients include standard essential micronutrients, and phosphite, and salicylate salts (Gottwald et al. 2012). Symptomatic trees are not removed and scouting for the disease is discontinued. As with Strategy 2, a strong psyllid control program is practiced. Roka, et al. (2010) have estimated that the per acre increase in grove maintenance costs associated with Strategy 3 ranges from $200 to $600 per acre depending on the type and amount of foliar nutritionals a grower decides to apply.

The primary concern among plant pathologists with Strategy 3 is that HLB inoculum is left unchecked. The economic implications of Strategy 3 include whether it is feasible for young trees (ages 3-8) to reach their productive maturity, whether planting the next generation of citrus trees is economically viable, and whether the presence of a grove following Strategy 3 while other growers follow Strategy 2 will cause increased damage on the latter growers' fields. Spatial analysis of disease spread in south Florida suggests that spread between citrus blocks is a more significant portion of disease spread than the spread of the disease within a citrus block (Gottwald et al. 2008). This suggests that heterogeneous control methods may reduce the viability of Strategy 2.

This study addresses the economic consequences of the three strategies. In other words, how does a grower determine which strategy is in her/his best interests (given average grove age and initial infection rate)? Strategy 1 needs to be considered as a baseline to reference Strategies 2 and 3. Growers make heterogeneous decisions regarding their choice among control strategies. Models are developed that allow economic assessment of each strategy and determine the scenarios for which each strategy is optimal or yield a positive net present value, considering tree age at first detection, and rates of infection at first detection. Since the optimal strategy may vary due to tree age at first detection and the rate of infection at first detection, the optimal strategy may vary across growers located nearby. Currently, the long term net present value of the control strategies is unknown because of uncertainty in the efficacy of the strategies. Our research identifies important efficacy targets that must be achieved for the long-term economic viability of a citrus grove. Our results provide a recommendation of the optimal control strategy for a given set of conditions such as the age of the planting and initial rate of infection.

HLB Disease Incidence, Latency, and Spread

Disease incidence has been estimated using a variety of approaches. Gottwald et al. (2010) determined disease incidence via a logistic spread rate per year calculated by linear regression of transformed (The disease incidence data was first transformed via a logistic linear function given by $\text{logit}(y) = \ln(y/1-y)$) disease incidence in Florida. HLB incidence in Florida has also been found in similar studies to increase within 10 months from 0.2 % to as much as 39 % (Gottwald et al. 2007b, 2008; Irey et al. 2008). Spatiotemporal spread models have also been used to characterize HLB in Florida where simultaneous within and across grove spread were common (Gottwald et al. 2008). Other studies have been conducted such as in Vietnam where HLB incidence is found to vary depending on the management strategy employed (Gatineau et al. 2006) or in Brazil where incidence has been shown to depend on proximity to HLB-infected citrus groves and/or on neighbors' behavior (Bassanezi et al. 2006; 2005, Gatineau et al., 2006; Gottwald et al., 2007a; 2007b). Albrecht et al. (2012) showed in a Florida study that HLB disease incidence is unaffected by the type of rootstock used in propagation.

Disease latency refers to the time between when infection by a pathogen occurs and the onset of symptoms. HLB latency has also been demonstrated in some studies where for every symptomatic tree in a given grove, 13 (range 2 to 56) HLB-positive but asymptomatic trees existed in its neighborhood, which expressed symptoms in subsequent assessments (Bassanezi et al. 2006). Irey et al. (2006) use PCR techniques to test for the presence of the bacteria that causes HLB (*Candidatus* Liberibacter asiaticus) in plots of about 190 trees and found that 60 percent more asymptomatic trees existed in addition to the symptomatic trees that were found (Irey et al. 2006). High correlation ($R^2 = 0.89$) between infected trees and total number of infected trees among the plots suggests natural disease transition from asymptomatic trees to symptomatic trees. In some instances, high bacteria titer was found with PCR in some asymptomatic trees, signifying the need for roguing asymptomatic trees as well (National Research Council, 2010, Irey et al. 2006). The presence of a high percent (80%) of infected trees within 25 m of a symptomatic tree also signifies short distance spread of HLB (Irey et al., 2006).

HLB progression in a grove has also been determined to depend on the vector population and inoculum levels as well as average grove age at first detection. HLB progression in Reunion Island, China, and the Philippines is reported to follow a sigmoid curve, with clustering of diseased trees (Gottwald and Aubert, 1991; Gottwald et al. 1989, 1991). In Reunion Island more aggregation towards the direction of prevailing wind was observed, suggesting that psyllids are drifted by the wind. Aggregation in China was facilitated by closer tree spacing. Logistic growth rates are more plausible for both growth of an infested area in space and population density growth than constant growth rates (Kompas and Che, 2009). This suggests that an infected area initially grows exponentially, slows down and finally stops as the potential range of the species is attained. Disease progression can reach asymptotic levels faster in young groves than older groves (Gottwald et al. 2007, 2007a). The dispersal distance for HLB-infected psyllids have been estimated to range from 0.88 to 1.61 km with a median of 1.58, which may imply that groves more than 2km apart are unlikely to directly affect each other with HLB (Gottwald et al., 2007b, Gottwald et al., 2008a). Thus HLB spread is spatially continuous and simultaneous, primarily via psyllid feeding behavior between groves and secondarily through within grove feeding of the psyllids, necessitating the need for landscape management practices for effective control. Manjunath et al. (2008) in a study to detect HLB bacteria from a sample of over 1,200 psyllid adults and nymphs in Florida found that the bacteria spread in an area may be detected one to several years before symptom development in plants.

The Economic Model

A citrus grove is an asset. We estimate the economic impact of HLB through its effect on the value of a particular citrus grove. There are a variety of approaches in asset valuation, but the most appropriate approach in this application is the income method. In the income method, future costs and revenues are estimated to give per annum net revenue. Future net revenue is discounted to the present to give net present value (NPV) using the formula,

$$NPV = \sum_{t=1}^{T} \frac{(P_t Q_t - C_t(Q_t))}{(1+r)^{t-1}}$$

Where P_t is price in time period *t*, Q_t is yield in time period *t*, C_t are costs in time period *t*, and *r* is the discount rate. HLB affects the NPV of an infected grove by increasing costs if control is implemented, and decreasing future fruit production, thereby reducing future revenues. Since the rate of spread depends in part upon the tree age at first infection, we compute NPV as a function of tree age as well as the level of infection at first detection. Since the NPV of a particular grove depends upon several factors, which are subject to random variation, stochastic dominance is an appropriate method to identify the superior strategy. At this time, however, knowledge of the underlying probability distributions of those random factors is not available, so our economic assessment is done in a deterministic framework.

The Biological Model

Our original idea to depict HLB spread was motivated by a Gompertz function as proposed by Bassanezi and Bassanezi (2008). This function specifies that the disease incidence, *y*, at time *t* is:

$$y_t^G = e^{\ln(y_0)e^{-\beta t}} \qquad (1)$$

Where y_0 is the disease incidence at first detection and β is the annual rate of spread of the disease. However, the Gompertz function always converges to 100% infection, which does not allow us to analyze control strategies that prevent 100% disease infection. We use the logistic function as it has the advantage of being more flexible and allows for a steady state level of disease infection that is less than 100%. In this case we estimate the parameters of the logistic function that approximate the Gompertz function, and use those parameters to estimate the impact of strategies 2 and 3. To do this, we use parameter values for y_0 and β for each age class from Bassanezi and Bassanezi (2008) to simulate Gompertz spread from low to high incidence until field incidence reaches 100%. Using nonlinear regression, the simulated Gompertz data for each age class are used to estimate the corresponding logistic β. Our logistic function is derived from the deterministic differential equation:

$$\frac{\partial Y}{\partial t} = \dot{Y} = \beta Y(1-Y), \qquad \dot{Y} = y_t^G - y_{t-1}^G, \qquad Y = y_t^G \qquad (2)$$

Where *Y* is the proportion of diseased trees at time *t*, $\dot{Y}$ is the change in the proportion of diseased trees and β is the annual rate of spread of the disease. The result of this procedure yielded our logistic β estimates to be 1.5148125, 0.8450625, and 0.4440625 of their Gompertz counterparts of 1.3, 0.65, and 0.325 obtained from Bassanezi and Bassanezi (2008), for each corresponding age class consisting of average grove age of 0, 3, and 6. The logistic curves are then generated according to (3):

$$Y_t = Y_{t-1} + \hat{\beta} Y_{t-1}(1 - Y_{t-1}) \quad (3)$$

For strategy 1, Y_t includes both symptomatic disease incidence, Y_t^s as well as asymptomatic disease incidence, Y_t^a. For strategy 2, we assume that trees remain asymptomatic for one year, implying that $\dot{Y}_t^s = \dot{Y}_{t-1}^a$. Further, we assume that all symptomatic trees are immediately removed once the tree exhibits symptoms, implying that Y_{t-1} in (3) equals Y_{t-1}^a. Since the disease moves both across trees in the grove and across canopy in a given infected tree, we need to model the spread of the disease in canopy area as well to determine the yield effect of HLB for strategies 1 and 3. We estimate the yield impact of HLB (r_t) as a function of symptomatic grove canopy area or disease severity X_t and yield of a healthy grove (R_t, average boxes per tree) for strategy 1 using the negative exponential model:

$$r_t^1 = R_t(e^{-bX_t}), \qquad X_t = \sum_{t=1}^{t}(\hat{y}_i^L - \hat{y}_{t-1}^L)x_{t-i}, \quad \text{i} = 1,2,....\text{t}; \quad (4)$$

$$x = 1/(1 + (1/x_0) - 1)e^{(-\theta t)}))$$

Where R_t equals 1, representing the full yield of a healthy grove (average boxes per tree), r_t^1 is the percent of healthy yield obtained for a given level of disease severity for strategy 1, b is the severity rate, X_t is total grove severity at time t, x is the fraction of HLB symptomatic tree canopy area at time t, x_0 is the fraction of HLB symptomatic tree canopy area at first detection, and θ is the annual rate of disease severity progress in an affected tree. For strategy 2, all symptomatic trees are removed, so the spread of yield losses through the canopy does not occur.

For strategy 3, the yield effect is assumed to be in between the yield effect for strategy 1 and a healthy grove. Since the reduction in yield relative to a healthy grove is unknown, we use averages between healthy yield and strategy 1's yield given by:

$$r_t^3 = \alpha r_t^1 + (1 - \alpha), \qquad \text{where } \alpha = 0.1, 0.2, 0.3, ... \quad (5)$$

With all three strategies modeled, we determine the scenarios for which each strategy would be optimal, considering all possible strategy efficacies and tree age and rates of infection at first detection.

Model Estimation Assumptions

We create disease spread curves using β values described above and use those parameters to estimate the NPV of strategies 1, 2, and 3. Given data on estimated boxes of fruit per tree by age group for non-Valencia oranges from the Florida Agricultural Statistics Service (Florida Citrus Statistics 2008-2009), the logistic curves are interacted with the investment or NPV model as specified above to estimate HLB impact on grower earnings based on tree age. Citrus prices are expressed in $/pound solids ($1.50/pound solid) with pound solids per box values dependent on tree age. The estimates are made on a per acre basis for a grower with 150 trees per acre and 100% original tree acreage remaining. We use a 10% discount rate for calculation of net present values. Operating and production costs for a mature grove include herbicide, pesticide, and fertilizer applications, irrigation, and pruning, but do not include HLB foliar nutritional sprays or pesticide applications for the baseline calculations. Since we assume no resetting (replacing trees lost in the citrus grove), the adjusted reset grove costs by tree age are assumed to be zero, as well as the establishment costs/acre for new solid set, the cost of tree removal and planting reset-replacement trees, reset frequency, and reset yield adjustments. Yield loss due to freeze or other diseases is assumed to be zero to avoid duplication.

We calculate net present value using a 15 year time horizon. Beyond 15 years, the net present value per year approaches zero. We calculate the net present value for groves with an initial average age ranging from 0 to 17. Beyond 17 years of age, tree yields no longer increase, so calculations for groves of this age represent our net present value upper bound.

Empirical Results of Model

Results are based on the baseline model. Key parameters such as the annual rate of spread of HLB (β), price per pound solids, latency, and yield compensation are fixed at specified values according to relevant literature and secondary data sources (Table 1).

Under strategy 1 (do nothing) almost all groves with an average tree age of 0 and 3 years yield a negative net present value at any initial disease incidence rate. Groves that contain younger trees at first detection have a lower net present value due to the faster spread of the disease in younger groves. Irrespective of the disease incidence rate at first detection, all groves with an average age of 6 years and over will yield a positive net present value. Table 2 reports the net present values for groves with rates of disease incidence varying from 0.1% to 50% and for average initial grove ages of 0, 3, 6, 10, 14, and 17 years. Figure 1 plots the net present values as a function of disease incidence and average age at first detection. It also contains contour lines, with the green contour line marking the ages and disease rates at which the net present value is zero.

Under tree removal (strategy 2), groves with average age of 0 display negative net present values whereas groves with an average age of 3 years show negative net present value when the initial disease incidence is 20% and larger. Groves with an average age of 6 show positive net present value for disease incidence ranging from 0.1% to 30%, but shows negative net present value for disease incidence of 40% and 50%. All other age categories show a positive net present value, no matter the initial rate of disease incidence (Table 3). In figure 2, the green contour line marks the ages and disease rates at which the net present value is $0.00 for strategy 2.

An enhanced foliar nutritional program (Strategy 3) is expected to boost yield of an HLB affected grove to levels close to that of a healthy tree. Results for this analysis that assume a yield penalty of 30% of a healthy grove are presented in Table 4. As before, only groves with average age of 0 show negative net present value at all levels of initial disease incidence. For this strategy, the ages and disease rates at which the net present value is zero are indicated by the green contour line of figure 3.

For ease of comparison, Tables 5 through 7 juxtapose the net present value for the three strategies for each age class. For groves whose average age is 0, although the net present values are all negative, Strategy 3 is superior to both strategies 1 and 2 at all rates of initial disease incidence except at the lowest incidence level of 0.1%, where strategy 2 is better than both strategy 3 and 1. Strategy 1 is also better than strategy 2 at all rates of initial disease incidence with the exception of disease incidence levels of 0.1% and 1.0%, at which strategy 2 is better than strategy 1. For trees with average age of 3 years, strategy 2 is better than strategies 1 and 3 when disease incidence ranges from 0.1% to 7.0%, and thereafter (incidence of 8.0% to 50%), strategy 3 is better than both strategies 1 and 2. For trees with average age of 6 and 10, strategy 1 is better than strategies 2 and 3 at lower rates of initial disease incidence (0.1% to 2.0%), after which strategy 2 becomes superior to strategies 1 and 3 when the disease incidence ranges between 3.0% and 10.0%. At the highest initial disease incidence of between 20% and 50%, strategy 3 is superior to strategy 2 and 1 in net present value. For trees with average age of 14 and 17, strategy 1 outperforms the other two strategies at the low rates of disease incidence (0.1% to 2.0%), and for the middle rates of disease incidence of between 3.0% and 8.0%, strategy 2 is better than the other two strategies. At the highest rates of initial disease incidence (10% to 50%), strategy 3 becomes superior to strategies 1 and 2.

Figure 4 delineates the ranges of initial grove age and initial disease incidence for which each strategy maximizes net present value. For almost new solid sets and groves with average age of 3, strategy 3 dominates at low initial disease incidence (1% to 7%), as well as at all other incidence levels (8% to 50%) for groves of almost all ages. Strategy 2 dominates for groves with average age of 3 years at low initial disease incidence of 0.1% to 2% and also at disease incidence levels of 3% to 7% for all groves with average age of 14. Strategy 1 dominates for all groves with average age of 11 only when disease incidence is 0.1% to 2%. Therefore, for almost all groves at almost all initial HLB disease incidence, there is the likelihood that the enhanced nutritional program will generate a higher NPV for the grower than if one were to follow a do nothing or tree eradication management strategy. For groves with average age of 14 years at initial HLB disease incidence of 3% to 7%, tree eradication program management strategy will yield higher returns to the grower than do nothing or implementation of the enhanced nutritional program. For groves at 11 years at very low HLB incidence (0.1% to 2%), the grower will be better off by doing nothing than either implementing the tree eradication or enhanced nutritional program. For new solid sets at any level of initial disease incidence, the enhanced nutritional program is likely to give the grower the best earnings on his/her investment than any other strategy. No matter how high the initial rate of disease incidence, each strategy remains positive in net present value for mature groves (groves with average age of 6 or larger). Strategy 3 performs even better especially for mature trees at almost all rates of disease incidence when the assumption on yield penalty of a healthy grove is 5%, 10%, or even 20% instead of the 30% yield penalty (Tables 4-7 to 4-9) used in the comparison. For all age classes, cost eventually exceeds revenue, especially for mature groves at high rates of initial disease incidence.

Conclusions

Which strategy is superior to the other(s) depends on the age of trees at first detection and the initial rate of disease incidence at first detection. Each strategy has its range of relevance region within which it maximizes a grower's net returns given the initial level of infection and the average age of the grove. Growers with newly established groves (average age of 0) and 3-year old groves at all levels of initial incidence of HLB and for all grove ages at 10% or more initial incidence may be better off implementing the enhanced nutritional program (strategy 3). For growers whose groves are 14 years in average age with initial HLB infection rate at 3% to 7%, the most obvious strategy should be strategy 2 (infected tree removal). Strategy 1 is the least optimal strategy and it is only optimal when incidence is very low (0.1% to 2%) for groves with average age of 11. In each of these scenarios, the grower's utility or welfare is maximized.

Table 1. Baseline Parameter Values

Parameter	Trees Age Class 0	3	6
Annual Rate of Spread of HLB (β)	1.51481250	0.84506250	0.44406250
Price/pound solid ($)	1.50000000	1.50000000	1.50000000
Latency Period (years)	1.00000000	1.00000000	2.00000000
Severity Rate of HLB (*b*)	3.68000000	1.84000000	0.92000000
Initial Severity (*s0*)	0.20000000	0.10000000	0.05000000

Table 2. NPV[1] for Strategy 1 (Do Nothing)

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	0	3	6	10	14	17
0.001	-2,614	3,843	11,463	14,551	16,487	17,101
0.010	-4,142	927	9,539	12,562	14,488	15,102
0.020	-4,532	-17	8,442	11,407	13,322	13,935
0.030	-4,696	-662	7,686	10,601	12,505	13,118
0.040	-4,779	-961	7,213	10,084	11,978	12,591
0.050	-4,942	-1,182	6,673	9,505	11,389	12,002
0.060	-5,004	-1,599	6,360	9,157	11,032	11,644
0.070	-5,052	-1,754	5,893	8,656	10,521	11,133
0.080	-5,089	-1,886	5,659	8,393	10,250	10,861
0.100	-5,140	-2,097	5,265	7,947	9,786	10,396
0.200	-5,338	-2,960	3,555	6,032	7,799	8,405
0.300	-5,369	-3,531	2,563	4,897	6,604	7,207
0.400	-5,462	-3,988	1,463	3,634	5,278	5,877
0.500	-5,482	-4,164	1,077	3,176	4,779	5,375

[1] Cumulative 15-year NPV ($/ac).

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 3. NPV[1] for Strategy 2 (Symptomatic Tree Removal)

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	0	3	6	10	14	17
0.001	-645	4,830	8,441	11,534	13,470	14,084
0.010	-4,050	4,322	8,207	11,276	13,204	13,818
0.020	-5,478	3,790	7,949	10,993	12,910	13,525
0.030	-6,302	3,287	7,694	10,712	12,620	13,235
0.040	-6,871	2,813	7,442	10,435	12,333	12,947
0.050	-7,297	2,363	7,193	10,160	12,049	12,663
0.060	-7,639	1,936	6,946	9,888	11,768	12,382
0.070	-7,916	1,531	6,701	9,619	11,489	12,103
0.080	-8,152	1,144	6,460	9,353	11,213	11,828
0.100	-8,529	423	5,983	8,828	10,670	11,284
0.200	-9,569	-2,411	3,745	6,359	8,111	8,725
0.300	-10,043	-4,421	1,721	4,124	5,790	6,404
0.400	-10,295	-5,937	-106	2,101	3,686	4,300
0.500	-10,433	-7,114	-1,752	276	1,784	2,399

[1] Cumulative 15-year NPV ($/ac).

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 4. NPV[1] for Strategy 3 (Enhanced Foliar Nutritional Program)

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	0	3	6	10	14	17
0.001	-2,170	3,030	7,822	10,915	12,852	13,466
0.010	-2,610	2,211	7,245	10,318	12,252	12,866
0.020	-2,727	1,872	6,916	9,972	11,902	12,516
0.030	-2,776	1,679	6,689	9,730	11,657	12,271
0.040	-2,826	1,589	6,547	9,575	11,499	12,113
0.050	-2,850	1,523	6,385	9,401	11,322	11,936
0.060	-2,868	1,398	6,291	9,297	11,215	11,829
0.070	-2,883	1,351	6,151	9,146	11,062	11,675
0.080	-2,894	1,312	6,081	9,067	10,981	11,594
0.100	-2,909	1,248	5,962	8,933	10,841	11,454
0.200	-2,968	989	5,449	8,359	10,245	10,857
0.300	-2,978	818	5,152	8,019	9,887	10,498
0.400	-3,006	681	4,822	7,640	9,489	10,099
0.500	-3,011	628	4,706	7,502	9,339	9,948

[1] Cumulative 15-year NPV ($/ac).

Yield from HLB infected trees reduced 30% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 5. NPV[1] for the Three Strategies for Age Classes 0 and 3

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	0			3		
	Strategy			**Strategy**		
	1	**2**	**3**	**1**	**2**	**3**
0.001	-2,614	-645	-2,170	3,843	4,830	3,030
0.010	-4,142	-4,050	-2,610	927	4,322	2,211
0.020	-4,532	-5,478	-2,727	-17	3,790	1,872
0.030	-4,696	-6,302	-2,776	-662	3,287	1,679
0.040	-4,779	-6,871	-2,826	-961	2,813	1,589
0.050	-4,942	-7,297	-2,850	-1,182	2,363	1,523
0.060	-5,004	-7,639	-2,868	-1,599	1,936	1,398
0.070	-5,052	-7,916	-2,883	-1,754	1,531	1,351
0.080	-5,089	-8,152	-2,894	-1,886	1,144	1,312
0.100	-5,140	-8,529	-2,909	-2,097	423	1,248
0.200	-5,338	-9,569	-2,968	-2,960	-2,411	989
0.300	-5,369	-10,043	-2,978	-3,531	-4,421	818
0.400	-5,462	-10,295	-3,006	-3,988	-5,937	681
0.500	-5,482	-10,433	-3,011	-4,164	-7,114	628

[1] Cumulative 15-year NPV ($/ac).

Yield from HLB infected trees reduced 30% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 6. NPV[1] for the Three Strategies for Age Classes 6 and 10

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	6			10		
	Strategy			**Strategy**		
	1	**2**	**3**	**1**	**2**	**3**
0.001	11,463	8,441	7,822	14,551	11,534	10,915
0.010	9,539	8,207	7,245	12,562	11,276	10,318
0.020	8,442	7,949	6,916	11,407	10,993	9,972
0.030	7,686	7,694	6,689	10,601	10,712	9,730
0.040	7,213	7,442	6,547	10,084	10,435	9,575
0.050	6,673	7,193	6,385	9,505	10,160	9,401
0.060	6,360	6,946	6,291	9,157	9,888	9,297
0.070	5,893	6,701	6,151	8,656	9,619	9,146
0.080	5,659	6,460	6,081	8,393	9,353	9,067
0.100	5,265	5,983	5,962	7,947	8,828	8,933
0.200	3,555	3,745	5,449	6,032	6,359	8,359
0.300	2,563	1,721	5,152	4,897	4,124	8,019
0.400	1,463	-106	4,822	3,634	2,101	7,640
0.500	1,077	-1,752	4,706	3,176	276	7,502

[1] Cumulative 15-year NPV ($/ac).

Yield from HLB infected trees reduced 30% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 7. NPV[1] for the Three Strategies for Age Classes 14 and 17

Disease Incidence at First Detection	Average Age of Trees at First Detection					
	14			17		
	Strategy			**Strategy**		
	1	**2**	**3**	**1**	**2**	**3**
0.001	16,487	13,470	12,852	17,101	14,084	13,466
0.010	14,488	13,204	12,252	15,102	13,818	12,866
0.020	13,322	12,910	11,902	13,935	13,525	12,516
0.030	12,505	12,620	11,657	13,118	13,235	12,271
0.040	11,978	12,333	11,499	12,591	12,947	12,113
0.050	11,389	12,049	11,322	12,002	12,663	11,936
0.060	11,032	11,768	11,215	11,644	12,382	11,829
0.070	10,521	11,489	11,062	11,133	12,103	11,675
0.080	10,250	11,213	10,981	10,861	11,828	11,594
0.100	9,786	10,670	10,841	10,396	11,284	11,454
0.200	7,799	8,111	10,245	8,405	8,725	10,857
0.300	6,604	5,790	9,887	7,207	6,404	10,498
0.400	5,278	3,686	9,489	5,877	4,300	10,099
0.500	4,779	1,784	9,339	5,375	2,399	9,948

[1] Cumulative 15-year NPV ($/ac).

Yield from HLB infected trees reduced 30% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 8. NPV[1] for the Three Strategies for Age Classes 0 and 3 at Different Yield Penalty[2] Levels for Strategy 3

Disease Incidence at First Detection	Average Age of Trees at First Detection									
	0					3				
	Strategy					Strategy				
	1	2	3			1	2	3		
			20%	10%	5%			20%	10%	5%
0.001	-2,614	-645	-1,535	-900	-582	3,843	4,830	3,477	3,924	4,147
0.010	-4,142	-4,050	-1,828	-1,046	-655	927	4,322	2,894	3,632	4,002
0.020	-4,532	-5,478	-1,906	-1,085	-675	-17	3,790	2,705	3,538	3,954
0.030	-4,696	-6,302	-1,939	-1,101	-683	-662	3,287	2,576	3,473	3,922
0.040	-4,779	-6,871	-1,955	-1,110	-687	-961	2,813	2,516	3,444	3,907
0.050	-4,942	-7,297	-1,988	-1,126	-695	-1,182	2,363	2,513	3,421	3,896
0.060	-5,004	-7,639	-2,000	-1,132	-698	-1,599	1,936	2,389	3,380	3,875
0.070	-5,052	-7,916	-2,010	-1,137	-701	-1,754	1,531	2,358	3,364	3,868
0.080	-5,089	-8,152	-2,017	-1,141	-702	-1,886	1,144	2,331	3,351	3,861
0.100	-5,140	-8,529	-2,027	-1,146	-705	-2,097	423	2,289	3,330	3,850
0.200	-5,338	-9,569	-2,067	-1,160	-715	-2,960	-2,411	2,117	3,244	3,807
0.300	-5,369	-10,043	-2,073	-1,169	-716	-3,531	-4,421	2,002	3,187	3,779
0.400	-5,462	-10,295	-2,092	-1,178	-721	-3,988	-5,937	1,911	3,141	3,756
0.500	-5,482	-10,433	-2,096	-1,180	-722	-4,164	-7,114	1,876	3,123	3,747

[1] Cumulative 15-year NPV ($/ac).

[2]Yield from HLB infected trees reduced 20%, 10% and 5% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 9. NPV[1] for the Three Strategies for Age Classes 6 and 10 at Different Yield Penalty[2] Levels for Strategy 3

Disease Incidence at First Detection	Average Age of Trees at First Detection									
	6					10				
	Strategy					Strategy				
	1	2	3			1	2	3		
			20%	10%	5%			20%	10%	5%
0.001	11,463	8,441	7,865	7,907	7,929	14,551	11,534	10,958	11,002	11,023
0.010	9,539	8,207	7,480	7,715	7,832	12,562	11,276	10,560	10,803	10,924
0.020	8,442	7,949	7,260	7,605	7,778	11,407	10,993	10,329	10,687	10,866
0.030	7,686	7,694	7,109	7,529	7,740	10,601	10,712	10,168	10,607	10,826
0.040	7,213	7,442	7,036	7,482	7,716	10,084	10,435	10,087	10,555	10,800
0.050	6,673	7,193	6,906	7,428	7,689	9,505	10,160	9,949	10,497	10,771
0.060	6,360	6,946	6,844	7,397	7,673	9,157	9,888	9,879	10,462	10,754
0.070	5,893	6,701	6,750	7,350	7,660	8,656	9,619	9,779	10,412	10,739
0.080	5,659	6,460	6,704	7,327	7,638	8,393	9,353	9,727	10,386	10,715
0.100	5,265	5,983	6,625	7,287	7,619	7,947	8,828	9,637	10,341	10,693
0.200	3,555	3,745	6,283	7,116	7,533	6,032	6,359	9,254	10,150	10,597
0.300	2,563	1,721	6,085	7,017	7,484	4,897	4,124	9,027	10,036	10,541
0.400	1,463	-106	5,864	6,907	7,429	3,634	2,101	8,775	9,910	10,478
0.500	1,077	-1,752	5,787	6,869	7,409	3,176	276	8,683	9,864	10,455

[1] Cumulative 15-year NPV ($/ac).

[2]Yield from HLB infected trees reduced 20%, 10% and 5% on "normal" yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

Table 10. NPV[1] for the Three Strategies for Age Classes 14 and 17 at Different Yield Penalty[2] Levels for Strategy 3

Disease Incidence at First Detection	Average Age of Trees at First Detection									
	14					17				
	Strategy					Strategy				
	1	2	3			1	2	3		
			20%	10%	5%			20%	10%	5%
0.001	16,487	13,470	12,895	12,939	12,961	17,101	14,084	13,509	13,553	13,575
0.010	14,488	13,204	12,495	12,739	12,861	15,102	13,818	13,110	13,353	13,475
0.020	13,322	12,910	12,262	12,622	12,802	13,935	13,525	12,876	13,236	13,417
0.030	12,505	12,620	12,099	12,541	12,762	13,118	13,235	12,713	13,155	13,376
0.040	11,978	12,333	12,015	12,488	12,735	12,591	12,947	12,629	13,102	13,349
0.050	11,389	12,049	11,876	12,429	12,706	12,002	12,663	12,490	13,043	13,320
0.060	11,032	11,768	11,804	12,393	12,688	11,644	12,382	12,418	13,007	13,302
0.070	10,521	11,489	11,702	12,342	12,672	11,133	12,103	12,316	12,956	13,287
0.080	10,250	11,213	11,648	12,315	12,649	10,861	11,828	12,261	12,929	13,263
0.100	9,786	10,670	11,555	12,269	12,626	10,396	11,284	12,168	12,883	13,240
0.200	7,799	8,111	11,158	12,070	12,526	8,405	8,725	11,770	12,683	13,140
0.300	6,604	5,790	10,919	11,951	12,466	7,207	6,404	11,531	12,564	13,080
0.400	5,278	3,686	10,653	11,818	12,400	5,877	4,300	11,265	12,431	13,014
0.500	4,779	1,784	10,554	11,768	12,375	5,375	2,399	11,164	12,380	12,988

[1] Cumulative 15-year NPV ($/ac).

[2]Yield from HLB infected trees reduced 20%, 10% and 5% on “normal” yield for strategy 3.

Beta (1) = 1.5148125 for the 0 Age Class; Beta (2) = 0.8450625 for age Class of 3; Beta (3) = 0.4440625 for Age Classes of 6 or Larger.

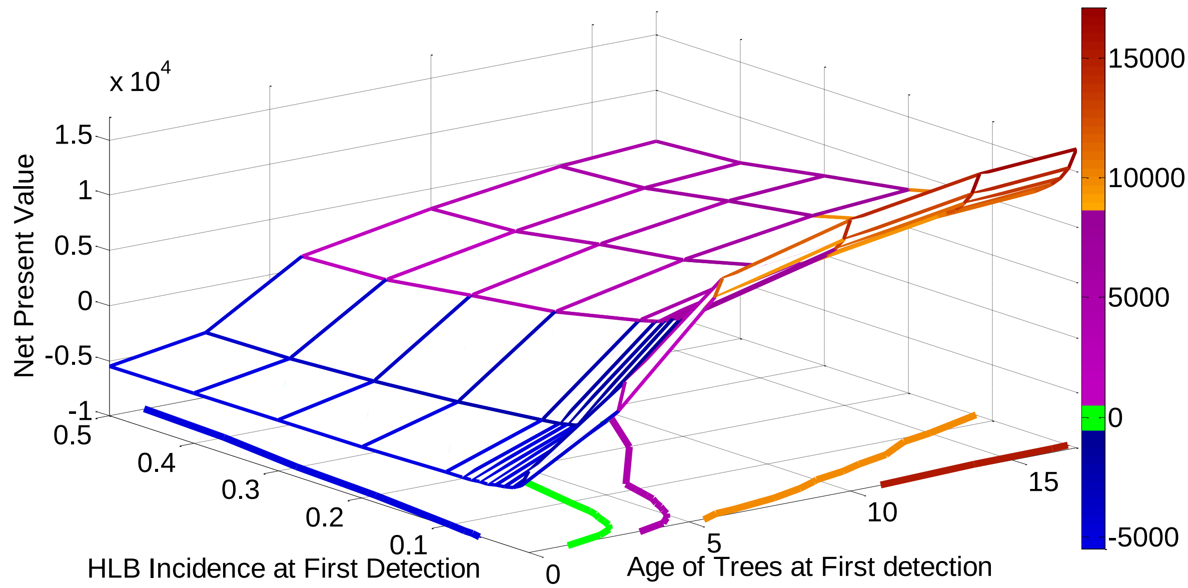

Figure 1. Net Present Value per Acre as a Function of Disease Incidence and Average Tree Age at First Detection with Contour Lines for the Do Nothing Strategy

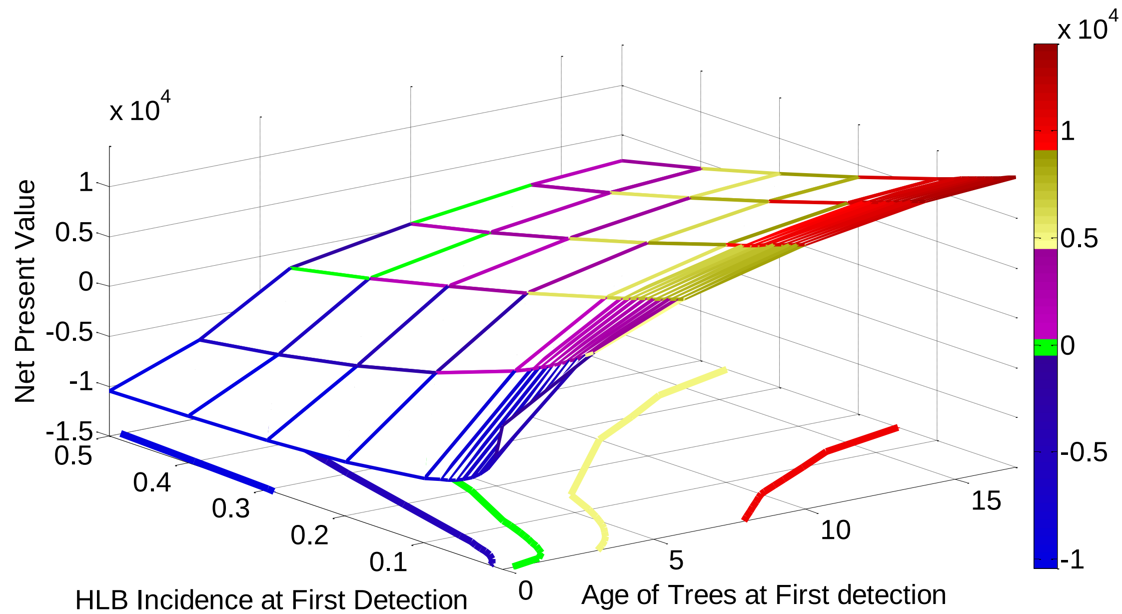

Figure 2. Net Present Value per Acre as a Function of Disease Incidence and Average Tree Age at First Detection with Contour Lines for Strategy 2

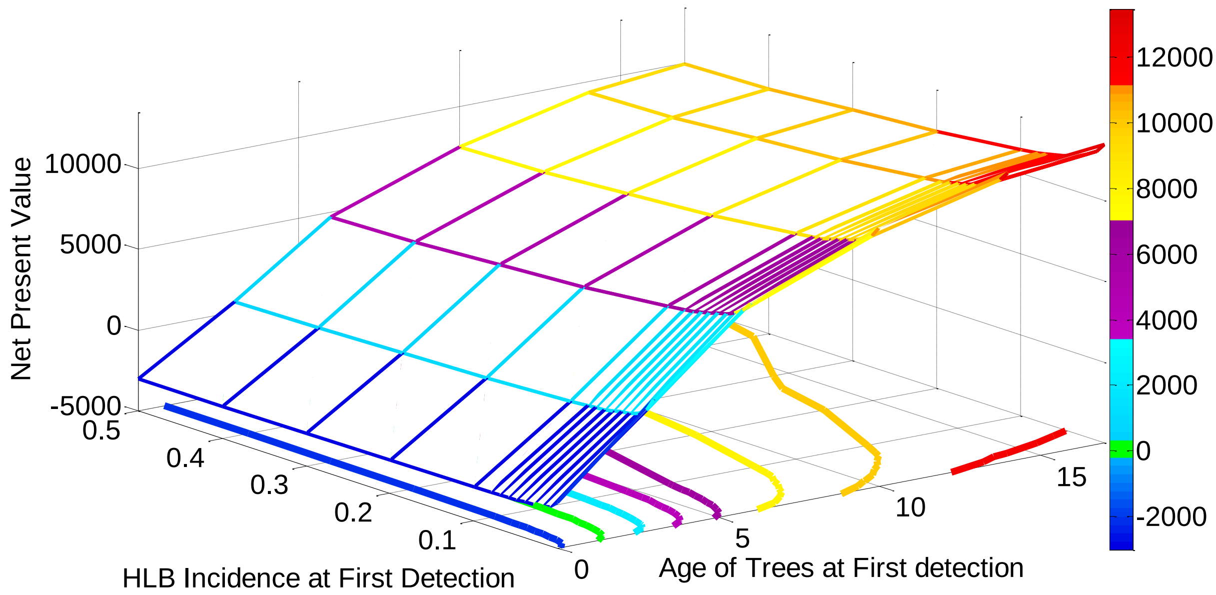

Figure 3. Net Present Value per Acre as a Function of Disease Incidence and Average Tree Age at First Detection with Contour Lines for Strategy 3 (30% Yield Penalty)

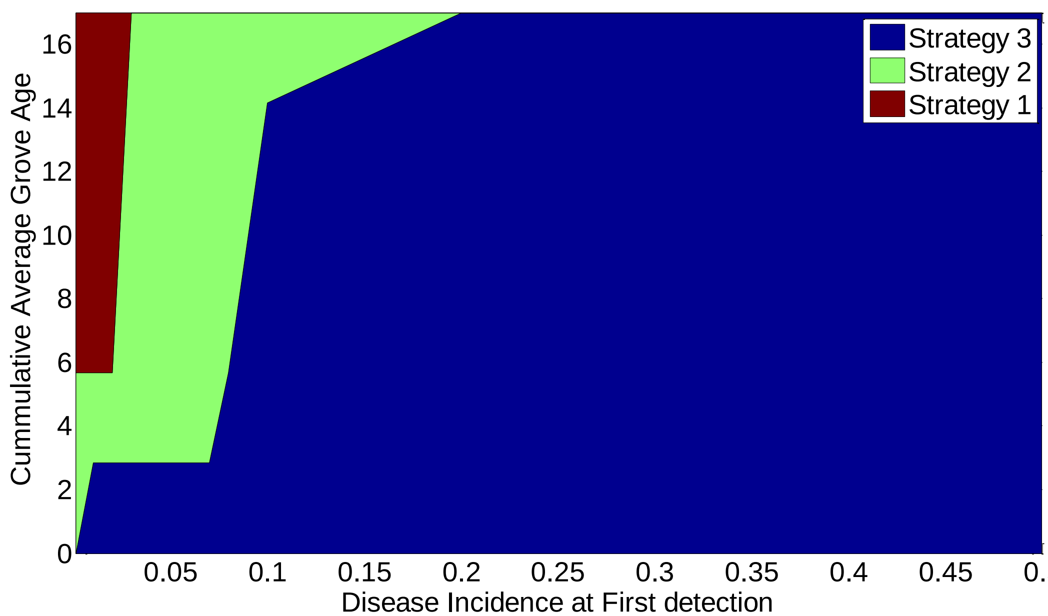

Figure 4. Dominant Strategy Given Disease Incidence at First Detection and Average Grove Age (Price = $1.50/ps, 30% yield penalty for strategy 3)

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