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The Economics of the Control Strategies of HLB in Florida Citrus

A.W. Salifu*, K. Grogan, T. Spreen, and F. Roka

University of Florida, IFAS, Food and Resource Economics Department, Gainesville, FL 32611

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Huanglongbing (HLB), also known as citrus greening, is a bacterial disease that affects all varieties of citrus. HLB was first discovered in Florida in 2005 and is now found in all counties where commercial citrus is produced. HLB bacteria are spread by a small leaf-feeding insect called the Asiatic citrus psyllid. The disease disrupts the phloem of the tree, causing the tree's decline and limiting its ability to uptake nutrients. Initial symptoms of HLB include yellowing of leaves, premature fruit drop, and small, misshapen fruit that contain bitter juice with no economic value. At the present time, there are three available strategies to cope with HLB. Strategy 1 is to do nothing, allowing the disease to spread while taking no measures to slow its spread or mitigate its impact. Strategy 2 implements an aggressive psyllid control program and a scouting program to identify symptomatic trees. Once found, symptomatic trees are eradicated. Strategy 3 initiates a strong psyllid control program but suspends the scouting and infected tree removal program and instead treats the symptoms of HLB through foliar application of micro- and macronutrients. This paper seeks to determine the profitability of each strategy given average grove age, age at first detection, and annual rate of spread of HLB.

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.

Florida is the leading citrus-producing state in the United States, with nearly 600,000 acres devoted to commercial production. HLB poses as the most serious obstacle faced by the state's $9 billion citrus industry, which supports almost 76,000 jobs. To appreciate the devastating impact of HLB on Florida citrus, it is said to cause far worse tree damage than citrus canker which was responsible for the destruction of over 4 million trees. Tree removal due to HLB infection has resulted in the reduction of approximately 10% of Florida's commercial citrus production, and 40% increased production costs (Irey et al., 2008). HLB has already been implicated for losses in land acres allocated to citrus in the state since 2006, and soaring grower costs in terms of tree eradication, psyllid control, inspections, and replanting costs (Tampa Bay Online, 2008). Hodges and Spreen (2012) estimated that within the last 5 years, Florida has lost 6,600 jobs, direct revenue of $1.3 billion, and indirect revenue of $3.6 billion, due to HLB. A more important, longer-term consequence has been the fact that HLB has created huge uncertainty among Florida citrus growers with respect to future investment/planting.

HLB is a disease with two important characteristics. First, the rate of spread is strongly affected by tree age because the psyllids prefer new growth (Brlansky et al., 2011). Young trees, which are more vigorous as compared to mature trees, produce more flushes and thereby are more susceptible to psyllid feeding and disease transmission. In the case of mature trees, the disease spreads more slowly (Gottwald, 2010). Consequently, an infected mature tree is capable of producing usable fruit for several years while at the same time serving as a source of infection for other healthy trees. Other factors which affect rate of spread include the size of the ACP population and the initial level of infection when the disease is found. Control through tree eradication is complicated by a latency period between the time a tree first becomes infected and when it expresses visual symptoms. Once a mature tree is infected, it may not begin to exhibit symptoms of the disease for up to 2 years. If the rate of infection in a particular grove is relatively high at the time the disease is first discovered, a policy of eradication of symptomatic trees may result in destruction of the entire grove.

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 hurricane Wilma. Later in 2005, an interdisciplinary team of U.S. 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 the citrus industry, the state or the USDA has not put in place a clear and decisive procedure for control of HLB, unlike in the case of the aborted citrus canker control program.

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 mitigate HLB's impact on tree health. This strategy represents a baseline from which to estimate the net benefits of Strategies 2 and 3. Strategy 1 has no effect on per acre costs as management tactics are not modified. Per acre revenues, however, are gradually decreased 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

*Corresponding author; phone: (352) 301-1691; email: wahab242001@yahoo.com

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, currently, is the only internationally accepted control strategy for HLB (Aubert, 1990). Under Strategy 2, an aggressive psyllid control program is put into place to suppress psyllid populations. Next, between 4 and 12 inspections are conducted annually to identify symptomatic trees. Once found, symptomatic trees are immediately eradicated (Brlansky et al., 2011). 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 four problems associated with Strategy 2. First, plant pathologists have yet to characterize the key parameters that would best 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 so 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.

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. Strategy 3 proposes to treat the symptoms of HLB through foliar application of micro- and macronutrients. The tree's defense response to an HLB infection is to produce compounds that block phloem vessels of the tree's vascular system. This damages the root system and inhibits the ability of the tree to uptake nutrients from the ground. 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 net present value than Strategy 2 even though Strategy 2 could successfully reduce HLB inoculums to a manageable base level. In the foliar feeding method, a portion of the nutritional needs of the tree is applied through foliar sprays including both macro- and micronutrients (Spann et al., 2010). 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 nearby growers follow Strategy 2 will cause increased damage in the Strategy 2 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.

The question to be addressed in this study is: what are the economic consequences of the three strategies? Strategy 1, do nothing, needs to be considered as a baseline to reference Strategies 2 and 3. Currently, the long term net present value of the control strategies is unknown because of uncertainty in the efficacy of the strategies. We built a bioeconomic model to identify the target control efficacies at which the net present value of the grove is positive and determine efficacy thresholds at which one strategy is preferred over the other. Once the efficacies of the strategies are known, our results will 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.

The Economic Model

A citrus grove is an asset. We estimated 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, particularly with respect to psyllid control, and also by decreasing future fruit production, thereby reducing future revenues. Since the rate of spread depends in part on the tree age at first infection, it will be necessary to 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 on 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 we shall proceed with our economic assessment 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:

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

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 intend to use the logistic function which 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 will estimate the parameters of the logistic function that are equivalent or approximate the Gompertz function, and use those parameters to estimate impact of Strategies 2 and 3. To do this, we use parameter values for y_0 and β from Bassanezi and Bassanezi (2008) to generate HLB disease incidence (y_t^G) for 20 years in one-year time steps. Our logistic function is derived from the deterministic differential equation:

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

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. We estimate this logistic function using nonlinear regression for $\hat{\beta}$ as a function of disease incidence at first detection and average age of the grove at first detection (Table 1). Our new logistic curves are then generated according to (3):

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

For Strategy 1, Y_t will include 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 the canopy in a given infected tree, we need to model the spread of the disease in the canopy area as well as 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/tree) for Strategy 1 using the negative exponential model:

$$r_t^1 = R_t(e^{-bX_t}), \qquad X_t = \sum_{i=1}^{t}(\hat{y}_i^L - \hat{y}_{i-1}^L)x_{t-i},$$
$$i = 1,2,\ldots t; \qquad \hat{y}_t^L = \frac{s_t}{Q},$$
$$x = 1/(1 + (1/x_0) - 1)e^{(-\theta t)}) \tag{5}$$

where R_t equals 1, representing the full yield of a healthy grove (average boxes/tree), r_t^1, is the percentage of healthy yield obtained for a given level of disease severity, X_t is total grove severity at time t, $\hat{y}_t^L$ is the proportion of symptomatic trees in the grove, 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, θ is the annual rate of disease severity progress in an affected tree, Q is total number of trees in the grove, and s is the number of symptomatic trees in the grove. 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 will 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 yield given by:

$$r_t^3 = ar_t^1 + (1 - \alpha), \text{ where } \alpha = 0.1, 0.2, 0.3, \ldots \ldots \ldots \tag{6}$$

Empirical Estimation

We create disease spread curves using β values of 1.300, 0.650, 0.325, and 0.244 for each of the 0–2, 3–5, 6–10, and over 10 years old age groups, respectively (Bassanezi et al., 2006; Catling and Atkinson, 1974; Gatineau et al., 2006; Gotwald et al., 1991, 2007a, 2007b), based on the Gompertz function. We then estimate the parameters of the logistic function that approximates the Gompertz function (Table 1), and use those parameters to estimate Strategies 1, 2, and 3. Given data on estimated boxes of fruit per tree by age group for both 'Valencia' and 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% of the 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, 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, the adjusted reset grove costs by tree age are set to 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 disease is set to zero to avoid duplication.

We calculate net present value using a 15-year time horizon. Beyond 15 years, the net present value per year goes towards 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.

Results and Discussion

Under Strategy 1 (do nothing) almost all groves with an average tree age less than 5 years yield a negative net present value at any initial disease incidence rate. Groves that contain younger

Table 1. Estimated logistic parameter approximates of the Gompertz function.

Disease incidence	Estimated beta for each age class		
at first detection	0–2	3–5	6–10
0.001	1.559	0.845	0.451
0.01	1.467	0.854	0.443
0.02	1.397	0.835	0.442
0.03	1.344	0.839	0.441
0.04	1.321	0.820	0.444
0.051	1.262	0.812	0.437
0.061	1.231	0.804	0.435
0.071	1.205	0.797	0.433
0.081	1.182	0.789	0.430
0.1	1.143	0.775	0.426
0.2	1.014	0.711	0.402
0.3	0.938	0.660	0.380
0.4	0.885	0.620	0.360
0.5	0.845	0.586	0.342

Table 2. Net present value[z] for Strategy 1 (do nothing).

Disease incidence at first detection	Avg age of trees at first detection: 0	3	6	10	14	17
0.001	–2737	3660	11663	14752	16689	17303
0.01	–4106	905	10220	13257	15184	15797
0.02	–4460	6	9174	12160	14076	14689
0.03	–4607	–650	8412	11352	13257	13870
0.04	–4706	–916	7769	10665	12561	13174
0.051	–4758	–1148	7276	10132	12018	12630
0.061	–4770	–1302	6865	9686	11562	12174
0.071	–4827	–1464	6508	9297	11164	11775
0.081	–4872	–1598	6193	8951	10810	11421
0.1	–4935	–1795	5681	8386	10229	10839
0.2	–4995	–2397	3951	6451	8221	8828
0.3	–5085	–2663	2923	5280	6991	7594
0.4	–5074	–2936	2185	4432	6093	6692
0.5	–5211	–3332	1606	3762	5379	5975

[z]Cumulative 15-year NPV ($/acre).

Table 3. Net present value[z] for Strategy 2 (symptomatic tree removal).

Disease incidence at first detection	Avg age of trees at first detection: 0	3	6	10	14	17
0.001	–841	4830	8441	11534	13470	14084
0.01	–3609	4308	8207	11276	13204	13818
0.02	–4432	3818	7951	10994	12912	13526
0.03	–4848	3312	7698	10716	12624	13238
0.04	–5319	2932	7442	10434	12333	12947
0.051	–5345	2507	7180	10146	12034	12649
0.061	–5509	2151	6940	9881	11760	12374
0.071	–5650	1820	6703	9621	11490	12104
0.081	–5776	1511	6471	9364	11225	11839
0.1	–5989	974	6038	8888	10731	11345
0.2	–6866	–1195	3951	6582	8338	8952
0.3	–7590	–2810	2107	4541	6215	6830
0.4	–8229	–4161	439	2693	4289	4904
0.5	–8794	–5350	–1094	990	2513	3127

[z]Cumulative 15-year NPV ($/acre).

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. The net present values plotted as a function of disease incidence and average age at first detection appear in Figure 1. It also contains contour lines, with the light blue areas marking the ages and disease rates at which the net present value is $0.00.

With tree removal (Strategy 2), groves younger than 2 years in average age display negative net present values whereas groves with average age 3 years show negative net present value when the initial disease incidence hits 20% and beyond. 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 areas mark the ages and disease rates at which the net present value is $0.00 for Strategy 2.

For ease of comparison, Tables 4 through 6 juxtapose the net present value for the two strategies for each age class. For trees younger than 2 years, Strategy 1 seems superior to Strategy 2, except at the lowest rates of initial disease incidence of 0.1%–2%. For trees with average age of 3 years, Strategy 2 is better than Strategy 1, except at the highest rates of disease incidence of 30%–50%. For trees with average age of 6 years or more, Strategy 1 is better than Strategy 2 at lower rates of initial disease incidence (0.1% to 5.1%), after which Strategy 2 becomes superior to Strategy 1 when the disease incidence ranges between 6.1% and 20%. Beyond disease incidence rates of 20%, Strategy 1 again becomes better than Strategy 2.

We also identified the percentage of the time (20-year period

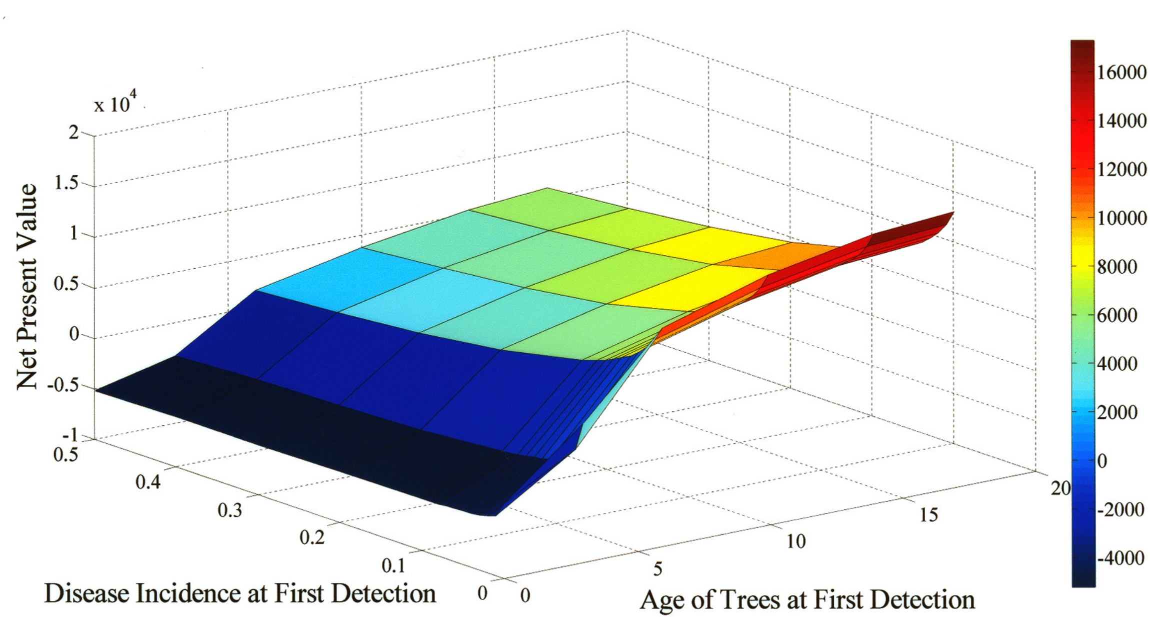

Fig. 1. Net present value per acre as a function of disease incidence and average tree age at first detection with contour lines for the do nothing strategy.

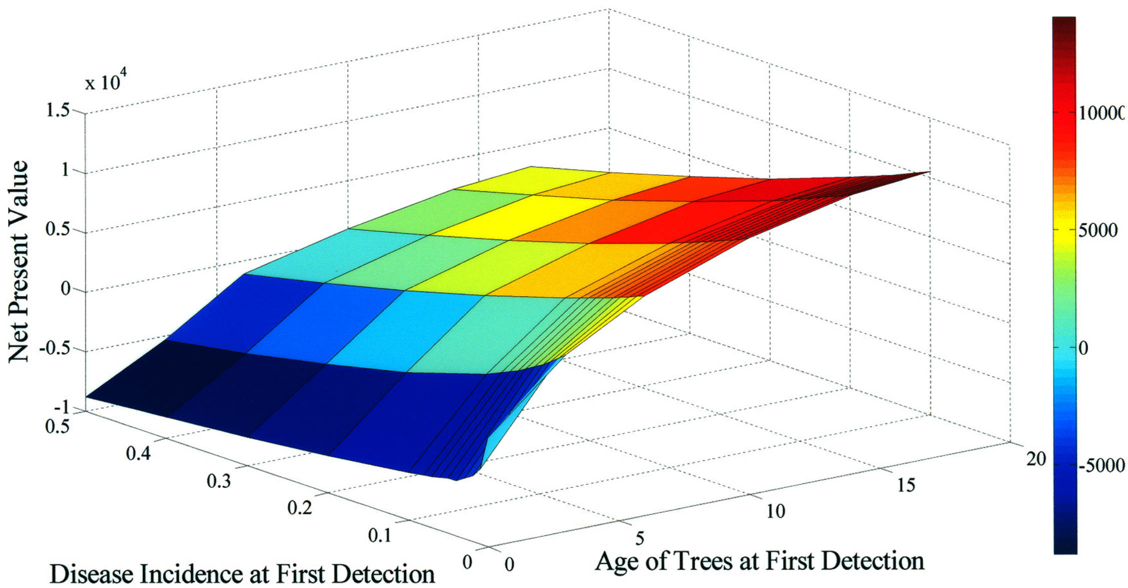

Fig. 2. Net present value per acre as a function of disease incidence and average tree age at first detection with contour lines for Strategy 2 (symptomatic tree removal).

Table 4. Net present value for the three strategies for age classes 0 and 3.

	Avg age of trees at first detection			
	0		3	
Disease incidence	Strategy		Strategy	
at first detection	1	2	1	2
0.001	–2737	–841	3660	4830
0.01	–4106	–3609	905	4308
0.02	–4460	–4432	6	3818
0.03	–4607	–4848	–650	3312
0.04	–4706	–5319	–916	2932
0.051	–4758	–5345	–1148	2507
0.061	–4770	–5509	–1302	2151
0.071	–4827	–5650	–1464	1820
0.081	–4872	–5776	–1598	1511
0.1	–4935	–5989	–1795	974
0.2	–4995	–6866	–2397	–1195
0.3	–5085	–7590	–2663	–2810
0.4	–5074	–8229	–2936	–4161
0.5	–5211	–8794	–3332	–5350

Table 5. Net present value for the three strategies for age classes 6 and 10.

	Avg age of trees at first detection			
	6		10	
Disease incidence	Strategy		Strategy	
at first detection	1	2	1	2
0.001	11663	8441	14752	11534
0.01	10220	8207	13257	11276
0.02	9174	7951	12160	10994
0.03	8412	7698	11352	10716
0.04	7769	7442	10665	10434
0.051	7276	7180	10132	10146
0.061	6865	6940	9686	9881
0.071	6508	6703	9297	9621
0.081	6193	6471	8951	9364
0.1	5681	6038	8386	8888
0.2	3951	3951	6451	6582
0.3	2923	2107	5280	4541
0.4	2185	439	4432	2693
0.5	1606	–1094	3762	990

of analysis) in which operating costs exceed revenue as a function of disease incidence and average tree age at first detection for all the two strategies (Figs. 3, 4). For groves with an average age of 2 years or less, operating costs exceeds revenue almost 100% of the time (Fig. 3). The percentage of the time in which cost exceeds revenue ranges from 45% to 100% for groves with average age of 3. For these young groves, production is small or none and the disease spreads quickly, preventing the grove from having positive net revenue. Cost exceeds revenue 0% to 70% of the time for groves with average ages of 6, 10, 14, and 17. However, even for mature groves, the disease spreads to a point where revenues no longer exceed costs. In Figure 4, for trees 2 years or younger, in 35% to 100% of the time, cost exceeds revenue, whereas cost never exceeds revenue for trees with average age of 3 or 6, 100% of the time, except at high rates of initial disease incidence (30% or more). In the more matured groves (10–17 average age cohorts), revenue exceeds cost 90% to 80% of the time, especially during the first 1 to 18 years.

Conclusions

Which strategy is superior to the other depends on the age of trees at first detection and the initial rate of disease incidence at first detection. For almost new, solid sets (less than 2 years old), Strategy 1 dominates, whereas Strategy 2 dominates for trees with average age of 3 years. For more mature trees (over 6 years), Strategy 1 dominates at low initial disease incidence that was considered in the analysis, followed by Strategy 2, which dominates when

Table 6. Net present value for the three strategies for age classes 14 and 17.

	Avg age of trees at first detection			
	14		17	
Disease incidence	Strategy		Strategy	
at first detection	1	2	1	2
0.001	16689	13470	17303	14084
0.01	15184	13204	15797	13818
0.02	14076	12912	14689	13526
0.03	13257	12624	13870	13238
0.04	12561	12333	13174	12947
0.051	12018	12034	12630	12649
0.061	11562	11760	12174	12374
0.071	11164	11490	11775	12104
0.081	10810	11225	11421	11839
0.1	10229	10731	10839	11345
0.2	8221	8338	8828	8952
0.3	6991	6215	7594	6830
0.4	6093	4289	6692	4904
0.5	5379	2513	5975	3127

initial disease incidence is in the middle ranges. At the highest initial disease incidence rates considered, Strategy 1 dominates. The lower the level of HLB incidence and the younger the tree, the more likely do nothing will generate a higher NPV than tree eradication. The higher the level of HLB incidence and the more mature the trees, the more likely tree eradication will generate a higher NPV than do nothing. For all age classes, cost eventually exceeds revenue, especially for mature groves at high rates of initial disease incidence. Preliminary results for Strategy 3, not yet available for this paper, make it the most dominant strategy over 1 and 2, at the highest rates of initial disease incidence and for mature groves.

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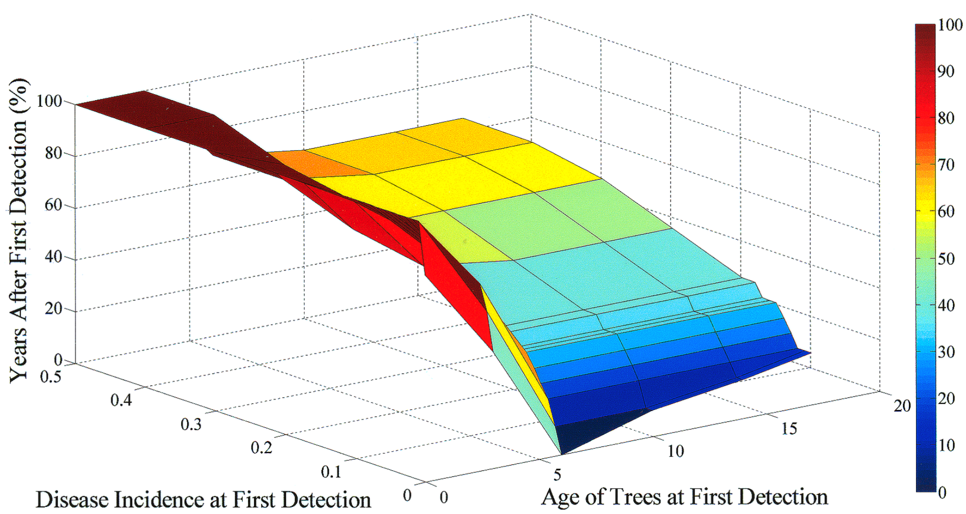

Fig. 3. Year at which operating costs exceed revenues as a function of disease incidence and average tree age at first detection for the do nothing strategy.

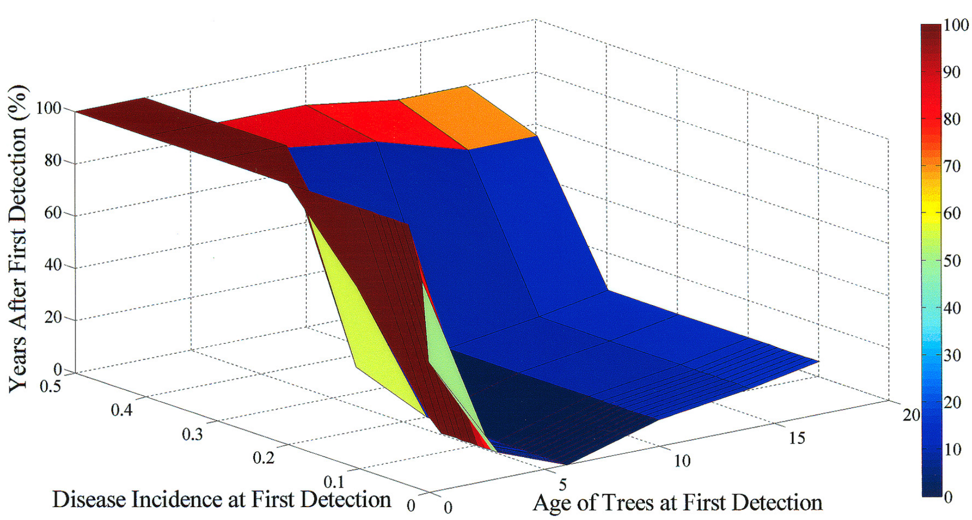

Fig. 4. Year at which operating costs exceed revenues as a function of disease incidence and average tree age at first detection for Strategy 2 (symptomatic tree removal).

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