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Economic Implications of Citrus Greening Disease Management Strategies

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Citrus greening (HLB) is an incurable bacterial disease severely affecting most citrus production regions. Evaluating the economic feasibility of control practices is challenging due to the complex intertemporal interactions among the pathogen, the vector, and the host. We propose a stochastic evaluation framework to systematically analyze the long-term economic performance of a broad range of management strategies. Different control approaches are evaluated in a hypothetical application in Texas. Results highlight the detrimental effects of the disease and the importance of developing cost-effective control options. A substantial loss in value is expected regardless of the intervention actions implemented.

Key words: *Candidatus Liberibacter asiaticus*, economic feasibility, epidemiology, equivalent annual annuity, Huanglongbing, Monte Carlo simulation, Texas

Introduction

Huanglongbing (HLB), or citrus greening disease, is a devastating disease of citrus worldwide. HLB originated in Asia and has spread worldwide through human movements of infected plant materials due to international trade, travel and migration (Gottwald, Aubert, and Zhao, 2010). In the United States, HLB is associated with *Candidatus Liberibacter asiaticus* (CLas), a phloem-inhabiting bacterium transmitted by the Asian citrus psyllid (ACP). Infected trees exhibit early abortion of fruits combined with small, lopsided, bitter, and green-bottomed fruits (da Graça, 1991; Gottwald, Aubert, and Zhao, 2010; Bassanezi et al., 2011). At present, HLB is an incurable disease, and it has become endemic in Florida and Texas; in California, a lower incidence has been observed in commercial groves (Singerman and Useche, 2016; Sétamou et al., 2020; Graham, Gottwald, and Sétamou, 2020).

The presence and risk of HLB outbreaks have lowered productivity, increased production costs, generated financial uncertainty, and promulgated the implementation of regional control programs (Salcedo et al., 2011; de Miranda, Adami, and Bassanezi, 2012; Singerman and Useche, 2016; Singerman, Burani-Arouca, and Futch, 2018; Trejo-Pech, Spreen, and Zansler, 2018). However, modest perceived effectiveness, disruptions to productivity, lack of coordinated efforts, and substantial increases in production costs have caused some growers to discontinue control strategies (de Miranda, Adami, and Bassanezi, 2012; Salifu et al., 2012; Singerman, Lence, and Useche, 2017). To guarantee broad adoption by growers, it is imperative to comprehensively evaluate the viability of conventional and novel control alternatives.

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In practice, evaluating the long-term economic feasibility of HLB management strategies is challenging. Given the devastating effects of HLB and its rapid spread, it is difficult to observe the natural evolution of the disease independent of control activities (Gottwald, Aubert, and Zhao, 2010). Additionally, government regulations may prohibit the evaluation of management strategies alongside appropriate no-treatment controls, even under experimental conditions (Bassanezi et al., 2011). As a result, comparing the effectiveness of available control strategies is done under expected disease progression scenarios without control for exogenous factors (Gottwald, da Graça, and Bassanezi, 2007; Bassanezi et al., 2011; Neupane, Moss, and van Bruggen, 2016; Singerman, Lence, and Useche, 2017). Modeling the progress and economic damage of the disease has its own set of challenges (National Academies of Sciences, Engineering, and Medicine, 2018). Given the current understanding of the CLas bacterium, it is difficult to represent the pathogen–host and vector–host interactions. Also, there is a considerable latency period in which bacteria concentrations remain very low and HLB symptoms are not expressed, making it difficult to positively identify infected trees. Further, citrus are perennial crops with a long, age-dependent productive life. This is of particular importance given that the intertemporal relationship between disease progression, control interventions, and resulting effects on yield vary as the grove matures. Economic models are expected to incorporate the inherent uncertainty of the disease and serve as a systems approach to complement HLB management (National Academies of Sciences, Engineering, and Medicine, 2018).

Additional research is needed to integrate the epidemiological and economic aspects of the disease. The main objective of this study is to develop a flexible, methodical framework to analyze the complex interactions between HLB spread, the effectiveness of management practices, and subsequent economic effects. We propose a stochastic model to analyze the economic feasibility and uncertainty of HLB control strategies. Compared to existing options, our model can handle a broad range of management practices and disease progression patterns. We present a clear track of the relationships between HLB incidence and severity, yield loss, effect of mitigation efforts, and economic outcomes. The proposed evaluation framework is illustrated under different management scenarios for grapefruit production in Texas.

Literature Review

At the farm level, the economic assessment of the damage caused by pests is often calculated in terms of the resulting net changes in revenue and production costs (Waterfield and Zilberman, 2012). The detrimental effect on yield is estimated proportionally to its counterpart level in the absence of the pest. The magnitude of the relative yield loss depends on pest pressure and control practices adopted. It is also assumed that the quality of the crop produced could be negatively affected by the pest and that the undesirable effects on quality are reflected in the price received. In terms of production costs, the implementation of pest control strategies is associated with additional expenses. The valuation framework is then used to either estimate the optimal use of pest management practices or to compare the economic feasibility of multiple pest control alternatives (Norton and Mullen, 1994). Simulation techniques are commonly used to analyze the economic risks related to pest management strategies (Greene et al., 1985; Pannell, 1991; Hyde et al., 2003).

Lower productivity due to reduced marketable yields and higher production costs caused by the adoption of control practices are the main economic burdens associated with HLB establishment in commercial citrus groves (Farnsworth et al., 2014). The first production losses attributed to HLB were documented in Asia and Africa in the 1900s (da Graça, 1991). These initial epidemics highlighted the rapid, destructive nature of the disease. Recent studies have quantified the observed and potential economic impacts of HLB in Florida (Court et al., 2017), California (Lopez and Durborow, 2014), Brazil (de Miranda, Adami, and Bassanezi, 2012), and Mexico (Salcedo et al., 2011).

In the United States, growers have followed a set of control practices recommended by the National Research Council (2010) to manage the disease progress, which includes ACP control, removal of infected trees, and ensuring the propagation of only pathogen-free nursery stocks. Some farmers have also adopted an enhanced fertilization regime (Farnsworth et al., 2014). In Texas, HLB management has relied on restricting the movement of citrus plant materials in and out of the commercial citrus zone and the implementation of an area-wide management (AWM) ACP control program (Sétamou, da Graça, and Prewett, 2012; Sétamou et al., 2020). The AWM program consists of coordinated insecticide spray applications within a specific geographic area during the dormant season and right before the beginning of the active growing season. The AWM program has been voluntarily implemented in more than 80% of all commercial citrus acreage, and a significant reduction in ACP populations has been observed in participating commercial groves and experimental trials (Sétamou, da Graça, and Prewett, 2012; Sétamou and Alabi, 2018).

Several attempts have been made to evaluate the economic feasibility of specific control and mitigation practices. Particularly, the profitability of establishing a new citrus grove and adoption of new planting incentive programs and higher tree densities in the presence of HLB have been extensively studied (Morris and Muraro, 2008; Spreen, Baldwin, and Futch, 2014; Spreen and Zansler, 2016; Singerman, Burani-Arouca, and Futch, 2018; Trejo-Pech, Spreen, and Zansler, 2018). Other studies have focused on new management practices aimed to slow the epidemic and prolong the productive lifespan of established citrus groves (Morris and Muraro, 2008; Belasque Jr et al., 2010; Salifu et al., 2012; Singerman, Lence, and Useche, 2017).

A common limitation of most economic analyzes of HLB is the use of an abbreviated epidemiological component. Typically, the intertemporal relationships among disease progress, yield loss, and effectiveness of control strategies are assumed constant (e.g., Roistacher, 1996). As a result, the chain effects caused by inherent disease developments or external actions on subsequent periods are omitted, which affects the accuracy of the economic estimates. Only a few economic studies have included HLB epidemiological principles in their yield and production cost projections (Salifu et al., 2012; de Miranda, Adami, and Bassanezi, 2012; Lopez and Durborow, 2014). However, important bioeconomic interactions have not been fully addressed, limiting the number of possible control strategies that can be evaluated. Our model proposes a set of interrelated and flexible functional forms to accommodate a diverse array of management practices and resulting stochastic effects on disease progress, yield loss, fruit quality, production cost, and long-term economic performance.

Stochastic Model

The proposed model, illustrated in Figure 1, is divided into two interrelated components: biological and economic modules. The biological module simulates the spread of HLB and the effectiveness of the proposed management practices under different production scenarios. The economic module uses the output generated by the biological module to assess the long-term economic feasibility of prescribed control strategies under different market conditions.

Biological Module

The biological module combines three interconnected components. First, an intertemporal production function is defined to represent the expected productivity without HLB incidence. This level of production is considered the baseline or the *ex ante* HLB yield. Second, the incidence and severity of the disease are modeled and the projected changes in productivity are calculated. Last, the foreseen effectiveness of current ACP and HLB management strategies is evaluated in terms of disease evolution, yield loss, and undesirable changes in fruit quality.

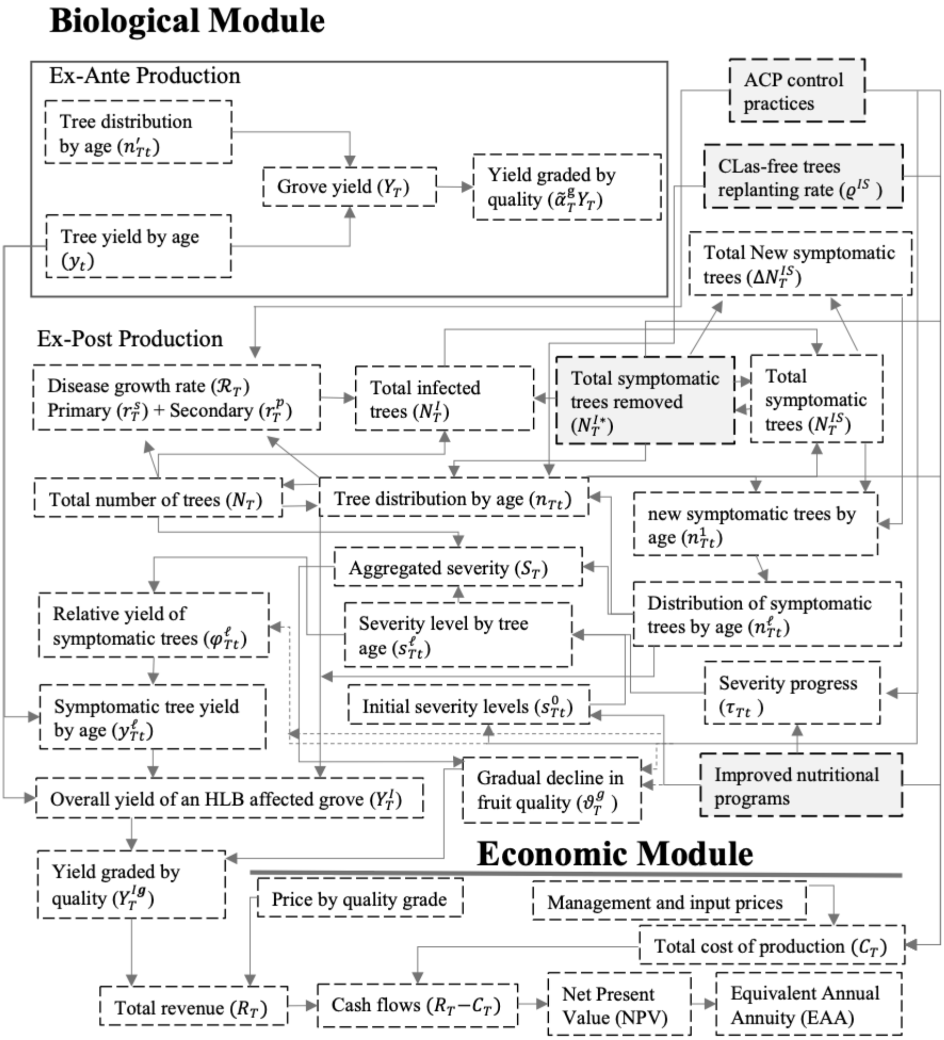

Figure 1. Citrus Greening Economic Evaluation Framework

Notes: Intervention actions are highlighted. Possible additional effects are represented by dashed arrows.

Ex Ante Production

The marketable yield of citrus is a function of the quantity and quality of the fruits produced. We assume that yield per tree follows the productive cycle described in Cheng (2007); Sauls (2008); de Miranda, Adami, and Bassanezi (2012); and Spreen and Zansler (2015), where the first commercial fruits are produced A years ($t = A$) after planting, peak production is reached in year $t = \tilde{p}$, production decline starts in year $t = \tilde{d}$, and the maximum productive lifespan of a tree is set to Ω' years. Specifically, the expected yield per tree is equal to

$$(1) \qquad y_t = \begin{cases} 0, & t < \mathrm{A} \\ \tilde{y}_{\mathrm{A}}, & t = \mathrm{A} \\ \tilde{y}_{\tilde{p}},, & \tilde{p} \le t < \tilde{d} \\ \tilde{y}_{\Omega'}, & t = \Omega' \end{cases},$$

and all other yields within the discrete levels described above are linearly interpolated. Tildes denote exogenous random variables. The output of these extrinsic stochastic variables does not depend on other variables considered in the analysis.

The observed total yield in a T-year-old grove is equal to

$$Y_T = \sum_{t=1}^{T} n'_{Tt}\left[y_t\left(1+\tilde{\imath}_t\right)\right], \tag{2}$$

where n'_{Tt} is the number of t-year-old trees before HLB occurrence and $\tilde{\imath}_t$ is a proportional, random-yield variability factor. The tree population age distribution is defined as a function of the annual tree mortality rate ($\tilde{m}$) and replanting rate (ϱ). Namely, the number of t-year-old trees in a T-year-old grove is given by

$$n'_{Tt} = \begin{cases} n'_{1,1} & T = t = 1 \\ \left[(1-\tilde{m})n'_{T-1,t-1}\right]^{1-\partial}\left(\varrho\tilde{m}N'_{T-1}\right)^{\partial} & T > 1,\ t \geq 1 \end{cases}, \tag{3}$$

where $\partial = 1$ if $t = 1$, and 0 otherwise; $n'_{1,1}$ is the initial planting density; and $N'_{T-1} = \sum_{t=1}^{T-1} n'_{T-1,t}$ is the total number of trees in the previous year. Note that $(1-\tilde{m})n'_{T-1,t-1}$ represents the surviving $t-1$-year-old trees from the preceding period, and $\varrho\tilde{m}N'_{T-1}$ is the total number of new trees planted in year T, which is proportional to overall tree mortality.

Based on quality, total yield (Y_T) is then classified into fresh and processed fruit. Small, irregular, and damaged fruits are processed and not considered for the fresh market. Fresh fruits are further graded based on their size and appearance.[1] In Texas, fresh grapefruits are graded as Texas Fancy and Texas Choice, of which Texas Fancy is considered of superior quality (U.S. Department of Agriculture, 2019b). Based on its grading, total yield is distributed as Texas Fancy, $\tilde{\alpha}_T^f Y_T$; Texas Choice, $\tilde{\alpha}_T^c Y_T$; and processed fruit, $\alpha_T^P Y_T$, where $\tilde{\alpha}_T^f$, $\tilde{\alpha}_T^c$, and $\alpha_T^P = 1 - \tilde{\alpha}_T^f - \tilde{\alpha}_T^c$ are the proportion of fruit sorted as Texas Fancy, Texas Choice, and processed, respectively.

HLB Incidence

After initial CLas infection in year Γ, there is a $\tilde{\delta}$-year delayed onset of HLB symptoms on infected trees, while asymptomatic trees serve as an infection focus shortly after initial contact with the CLas bacterium (Lee et al., 2015). The initial number of infected trees in year Γ is equal to $\tilde{N}_{\Gamma 0}^I$. The annual spread of the disease between trees is modeled using a logistic function. Specifically, the solution to the Verhulst differential equation was adapted, which is frequently used in ecology to model population growth (Brauer and Castillo-Chavez, 2012). The total number of infected (symptomatic and asymptomatic) trees in year $T > \Gamma$ is given by

$$N_T^I = \frac{N_T\left[(1-\tilde{m})N_{T-1}^I - N_T^{I*}\right]e^{\mathcal{R}_T}}{N_T + \left[(1-\tilde{m})N_{T-1}^I - N_T^{I*}\right]\left(e^{\mathcal{R}_T}-1\right)}, \tag{4}$$

where N_T is the total number of trees in year T, $N_T^{I^*}$ is the total number of infected trees removed in year $T > \Gamma + \tilde{\delta}$, and $\mathcal{R}_T$ is the disease growth rate. Comparable sigmoid functions have been used to model HLB incidence over time (Gottwald, 1989; Bassanezi and Bassanezi, 2008; Salifu et al., 2012), but equation (4) relaxes the assumptions about the duration of the disease latency period and offers the flexibility to incorporate annual changes in the stock of trees, the rate at which HLB spreads, and tree eradication decisions. Therefore, it is possible to model multiple combinations of control actions and intervention times.

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[1] Fruit-size grading is omitted in the analysis due to limited available historical data.

Under the presence of HLB, the stock of trees in a grove (N_T) depends not only on the *ex ante* mortality and replanting rates but also on current HLB management practices related to the removal and replanting of detected infected trees. Hence, the total number of trees in year $T \geq \Gamma$ is equal to

$$N_T = [1 + \tilde{m}(\varrho - 1)]N_{T-1} + \left(\varrho^{IS} - 1\right) N_T^{I*}, \quad \varrho^{IS} \geq 0, \tag{5}$$

where ϱ^{IS} is the relative replanting rate of removed symptomatic trees and $N_T = N'_T$ before the initial HLB incident year (i.e., $T < \Gamma$). Compared to *ex ante* conditions, the number of trees of a given age in an infected grove is given by

$$n_{Tt} = \left[(1 - \tilde{m})n_{T-1,t-1} - \frac{\lambda_T}{1 - \lambda_T} \sum_{\substack{\ell=1 \\ t>\tilde{\delta}}}^{t-\tilde{\delta}} n_{Tt}^{\ell}\right]^{1-\partial} \left(\varrho\tilde{m}N_{T-1} + \varrho^{IS} N_T^{I*}\right)^{\partial}, \tag{6}$$

where n_{Tt}^{ℓ} is the number of surviving t-year-old trees that have been symptomatic for ℓ years (equation 10), $n_{Tt} = n'_{Tt}$ if $T < \Gamma$, and λ_T is the removal rate of symptomatic trees, which is a function of the detection method employed.[2]

The removal of infected trees is aimed to reduce the spread of the disease at the expense of losing the potential yield of the trees removed. Therefore, the total number of infected trees removed is given by

$$N_T^{I*} = \lambda_T N_T^{IS}, \tag{7}$$

where N_T^{IS} is the number of symptomatic trees in year T:

$$N_T^{IS} = (1 - \tilde{m})\left(N_{T-1}^{IS} - N_{T-1}^{I*}\right) + (1 - \tilde{m})^{\tilde{\delta}} \Delta N_{T-\tilde{\delta}}^{I}. \tag{8}$$

Note that the number of trees depicting HLB symptoms is equal to surviving symptomatic trees from the previous year, plus those trees that were initially infected in year $T - \tilde{\delta}$ (i.e., $\Delta N_{T-\tilde{\delta}}^{I}$),[3] and started presenting the symptoms in year T. New symptomatic trees, $\Delta N_T^{IS} = (1 - \tilde{m})^{\tilde{\delta}} \Delta N_{T-\tilde{\delta}}^{I}$, are allocated among symptomatic prone trees (i.e., $(1 - \tilde{m}) \sum_{t=\tilde{\delta}+1}^{T} (n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell})$) based on the propensity of young ($t \leq \gamma$) and mature ($t > \gamma$) trees to start depicting HLB symptoms. Particularly, it is assumed that

$$\Delta N_T^{IS} = (1 - \tilde{m}) \left[\eta_T \sum_{t=\tilde{\delta}+1}^{\gamma} \left(n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right) + \beta_T \sum_{t=\gamma+1}^{T} \left(n_{T-1,t-1} - \sum_{\ell=1}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right)\right], \tag{9}$$

where $\eta_T \leq 1$ and $\beta_T \leq 1$ are the probability that younger and mature trees are symptomatic in year T, respectively, and it is expected that $\eta_T \geq \beta_T$. Moreover, the number of surviving symptomatic trees of a given age is equal to

$$n_{Tt}^{\ell} = \left[(1 - \tilde{m})(1 - \lambda_T) n_{T-1,t-1}^{\ell-1}\right]^{1-\xi} \left(n_{Tt}^{1}\right)^{\xi}, \ell \leq t - \tilde{\delta}, \tag{10}$$

where $\xi = 1$ if $\ell = 1$, and 0 otherwise; and n_{Tt}^{1} is the number of surviving, new symptomatic t-year-old trees in year T.[4]

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[2] Based on actual commercially available HLB detection methods, it is assumed that HLB can only be confirmed on symptomatic trees and the accuracy of the process depends on the method used (Arredondo Valdés et al., 2016).

[3] It can be shown that the number of new trees infected each year is equal to $\Delta N_T^{I} = N_T^{I} - [(1 - \tilde{m})N_{T-1}^{I} - N_T^{I*}]$.

[4] Namely, n_{Tt}^{1} is equal to $\eta_T(1 - \tilde{m})(1 - \lambda_T)(n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell})$ for younger trees and equal to $\beta_T(1 - \tilde{m})(1 - \lambda_T)(n_{T-1,t-1} - \sum_{\ell=1}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell})$ for mature trees.

Empirical evidence also suggests that the observable progression of HLB is a function of both primary and secondary infection spreads (Gottwald, Aubert, and Zhao, 2010). The primary spread refers to new infections that originated from hosts outside the grove, while the secondary spread is associated with CLas bacteria already present in the grove (or community spread). Hence, the disease growth rate ($\mathcal{R}_T$) in equation (4) is defined as

$$\mathcal{R}_T = r_T^p + r_T^s, \tag{11}$$

where r_T^p and r_T^s are the primary and secondary disease growth rate components, respectively. We further assume that the primary spread depends on external and endogenous factors (e.g., coordinated control efforts, grove age, and location) and the secondary spread growth rate varies based on the age of trees (Bassanezi and Bassanezi, 2008). Particularly, a faster rate is expected in younger trees than in older trees because younger trees are more prone to ACP infestation and hence CLas infection due to their tendency to produce more citrus flush shoots, which are preferred by the psyllids, compared to mature trees (Gottwald, Aubert, and Zhao, 2010; Sétamou and Alabi, 2018). Particularly, the primary disease growth rate is adjusted by the proportion of younger trees ($t \leq \gamma$):

$$r_T^p = \tilde{a}_{0,T} + \tilde{a}_{1,T} \frac{\sum_{t=1}^{\gamma} n_{Tt}}{N_T}, \tag{12}$$

where $\tilde{a}_{0,T}$ and $\tilde{a}_{1,T}$ are function parameters. The secondary growth rate is set as a linear function of the tree age distribution:

$$r_T^S = \sum_{t=1}^{T} \mu_{Tt} (1 + \tilde{\nu}_t) \frac{n_{Tt}}{N_T}, \tag{13}$$

where μ_{Tt} and $\tilde{\nu}_t$ are the expected secondary disease growth rate and proportional growth rate variability factor, respectively.

HLB Severity

HLB severity is typically measured as the proportion of the tree canopy visibly affected by the disease (Aubert et al., 1984; Regmi and Lama, 1988; Gottwald, 1989; Bassanezi et al., 2011). A particular characteristic of HLB is that visible symptoms are observed $\tilde{\delta}$ years after initial infection (da Graça, 1991; Gottwald, 1989; Gottwald, Aubert, and Zhao, 2010). We assumed that initial severity level ($s_{Tt}^0 = \bar{s}_{Tt}^0 (1 + \tilde{\varsigma}_t)$) as well as the annual rate of severity progress ($\tau_{Tt} = \bar{\tau}_{Tt}(1 + \tilde{\zeta}_t)$), $T > \Gamma + \tilde{\delta}$, vary with tree age, where $\bar{s}_{Tt}^0$ and $\bar{\tau}_{Tt}$ are the corresponding expected values and $\tilde{\varsigma}_t$ and $\tilde{\zeta}_t$ are stochastic severity variability factors. Similar to HLB incidence, a higher initial severity level and a faster progress is expected in younger trees compared to mature trees (Bassanezi and Bassanezi, 2008; Gottwald, Aubert, and Zhao, 2010). Particularly, the severity level of a t-year-old tree that has been symptomatic for ℓ years is assumed to be described by a logistic function:

$$s_{Tt}^{\ell} = \left[1 + \left(\frac{1}{s_{T-1,t-1}^{\ell-1}} - 1\right) e^{-\tau_{Tt}}\right]^{-1}, \ell \leq t - \tilde{\delta}, T > \Gamma + \tilde{\delta}. \tag{14}$$

Compared to Bassanezi and Bassanezi (2008), equation (14) allows for incorporating the intertemporal effects of intervention actions on the disease severity level through changes in the annual rate of severity progress.

A severity index is created to assess the aggregated HLB severity in a grove. Particularly, in year T, the overall severity is equal to

$$S_T = \frac{\sum_{t=1}^{T} \sum_{\ell=1}^{t} s_{Tt}^{\ell} n_{Tt}^{\ell}}{N_T}, T \geq \Gamma + \tilde{\delta}. \tag{15}$$

This index can be seen as the proportion of the total grove canopy exhibiting HLB symptoms; as documented in field studies, yield productivity is inversely correlated with the proportion of the canopy affected by the disease (Aubert et al., 1984; Bassanezi et al., 2011).

Ex Post Yield

The yield of symptomatic trees is progressively reduced based on their age and the number of years that they have been infected. Hence, the relative yield (φ^{ℓ}_{Tt}) of symptomatic trees associated with the evolution of the disease is modeled in terms of HLB severity (s^{ℓ}_{Tt}) using a generalized logistic function:

$$\varphi^{\ell}_{Tt} = 1 + \frac{\tilde{K} - 1}{\left(1 + Qe^{-\tilde{B}s^{\ell}_{Tt}}\right)^{1/v}}, \ell \le t - \tilde{\delta}, \tag{16}$$

where $\tilde{K}$, Q, $\tilde{B}$, and v are function parameters (Richards, 1959, Appendix A). Compared to the exponential yield loss function suggested by Bassanezi and Bassanezi (2008) and Bassanezi et al. (2011) and broadly adopted in the current literature (e.g., Salifu et al., 2012; de Miranda, Adami, and Bassanezi, 2012; Lopez and Durborow, 2014), equation (16) is flexible enough to avoid over-penalizing yield at lower HLB severity levels. Empirical observations suggest a modest yield loss during the first years of the disease, which intensifies until reaching a lower asymptotic level ($\tilde{K}$) at the pinnacle of severity (Catling and Atkinson, 1974; Aubert et al., 1984; Regmi and Lama, 1988). Additionally, the proposed relative yield function varies with tree age and the control practices adopted via the rate of severity progress (τ_{Tt}). That is, higher severity progress rates and therefore faster tree decay are associated with younger trees and no disease intervention conditions (Bassanezi and Bassanezi, 2008).

Therefore, the yield of a t -year-old tree that has been symptomatic for ℓ years is defined in terms of its corresponding stochastic *ex ante* yield (i.e., $y_t(1 + \tilde{\imath}_t)$) scaled downward by the relative yield loss function:

$$y^{\ell}_{Tt} = y_t\left(1 + \tilde{\imath}_t\right)\varphi^{\ell}_{Tt}, \ell \le t - \tilde{\delta}. \tag{17}$$

The overall yield of an HLB affected grove is the sum of the yield of both asymptomatic and symptomatic trees:

$$Y^{I}_{T} = \sum_{t=1}^{T}\left[\left(n_{Tt} - \sum_{\substack{\ell=1\\ t>\tilde{\delta}}}^{t-\tilde{\delta}} n^{\ell}_{Tt}\right) y_t\left(1 + \tilde{\imath}_t\right)\right] + \sum_{t=\tilde{\delta}+1}^{T}\sum_{\ell=1}^{t-\tilde{\delta}} n^{\ell}_{Tt} y^{\ell}_{Tt}, T \ge \Gamma + \tilde{\delta}. \tag{18}$$

In terms of fruit quality, the incidence of HLB is expected to affect the distribution of fruits graded for the fresh and processed markets. HLB symptomatic trees have been documented to yield a higher proportion of smaller, lighter, and more acid fruits (Bassanezi, Montesino, and Stuchi, 2009; Bassanezi et al., 2011). The detrimental impact of HLB on fruit quality is assumed to be a function of the aggregated severity index described in equation (15). A modest effect is expected at lower severity levels, but a faster decline in quality is observed as the disease progress through the grove canopy (Bassanezi et al., 2011). To consider the gradual decline in fruit quality, it is assumed that the relative change in the proportion of Texas Fancy and Texas Choice fruits produced in year T in an HLB affected grove is represented by generalized logistic functions:

$$\vartheta^{f}_{T} = 1 + \frac{\tilde{K}^{f} - 1}{(1 + Qe^{-\tilde{B}^{f}s_T})^{1/v}} \text{ and } \qquad \vartheta^{c}_{T} = 1 + \frac{\tilde{K}^{c} - 1}{(1 + Qe^{-\tilde{B}^{c}s_T})^{1/v}}, \tag{19}$$

respectively, which use, without loss of generality, a similar parameterization as in equation (16). The corresponding total Texas Fancy, Texas Choice, and processed fruit outputs after HLB incidence are given by

$$\begin{aligned} Y_T^{If} &= \vartheta_T^f \tilde{\alpha}_T^f Y_T^I, \\ Y_T^{Ic} &= \left[\left(1 - \vartheta_T^f\right) \tilde{\alpha}_T^f + \vartheta_T^c \tilde{\alpha}_T^c \right] Y_T^I, \text{ and} \\ Y_T^{IP} &= \left\{ 1 - \vartheta_T^f \tilde{\alpha}_T^f - \left[\left(1 - \vartheta_T^f\right) \tilde{\alpha}_T^f + \vartheta_T^c \tilde{\alpha}_T^c \right] \right\} Y_T^I, \end{aligned} \tag{20}$$

respectively. Note that fruit no longer graded as Texas Fancy is assumed to be graded as Texas Choice, and so forth.

ACP and HLB Management Practices

In general, available control and management practices focus on reducing CLas bacterium levels, controlling the vector, and mitigating disease symptoms (Gottwald, Aubert, and Zhao, 2010; National Research Council, 2010; Farnsworth et al., 2014). The effectiveness and limitations of current HLB control alternatives have been broadly discussed in the literature (Aubert et al., 1984; Belasque Jr et al., 2010; Gottwald, Aubert, and Zhao, 2010; Salifu et al., 2012; Shen et al., 2013; Farnsworth et al., 2014; Johnson and Bassanezi, 2016; Singerman, Lence, and Useche, 2017).

The stochastic functional forms of the biological module can be adjusted to represent the expected intertemporal relationships between HLB incidence and severity and their subsequent impacts on yield and fruit quality. Also, specific parameters of the models can be tuned to accommodate the distortions in the disease's progress caused by the adoption of specific ACP and HLB control and management strategies. For instance, the removal rate of HLB-symptomatic trees (λ_T) directly affects the disease's spread by altering the original CLas bacterium pool at any determined point in time. Similarly, the relative replanting rate of removed symptomatic trees with certified CLas-free trees (ϱ^{IS}) resets the maximum number of trees that can be infected each year. Additionally, tree resetting efforts will indirectly speed up HLB incidence and severity as the magnitude of disease growth rate ($\mathcal{R}_T$), initial severity level (s_{Tt}^0), and the rate of severity progress (τ_{Tt}) are greater in younger trees than in to mature trees. Changes in tree age distribution will further impact the overall productivity of an infected grove (Y_T^I).

Interventions aimed at controlling the vector or impeding its ability to transmit CLas could delay the disease's incidence and severity. Specific adjustments to the primary and secondary incidence growth rates (r_T^p, r_T^s), initial severity level (s_{Tt}^0), and the rate of severity progress (τ_{Tt}) can be made to accommodate the expected effects of implementing a new ACP control regime on the evolvement of HLB. Further, certain ACP management practices such as an increase in the number of insecticide applications could also reduce population levels and the economic damage caused by other pests (e.g., rust mites, spider mites, scales, leaf miners and thrips). As a result, controlling for ACP may also indirectly improve the yield and overall grading of the fruits produced. Parameters defining the shape of the relative yield of symptomatic trees (φ_{Tt}^ℓ) as well as the relative changes in the proportion of the different fruit grades associated with the progression of the disease ($\vartheta_T^f, \vartheta_T^c$) could be modified to account for the projected impacts that controlling the vector may have on yield and fruit quality, respectively.

Although the long-term effectiveness of current practices intended to lessen HLB symptoms has been questioned (Gottwald, Aubert, and Zhao, 2010), some farmers have opted for enhanced foliar fertilizer programs instead of CLas- or vector-oriented control methods (Salifu et al., 2012; Farnsworth et al., 2014). In this case, the sole adoption of a novel nutritional regime may not affect the evolution of HLB incidence but it could slow down the severity progress and improve yield and quality, at least in the short run. Hence, the adoption of a new nutritional program could be modeled through changes on the initial severity level (s_{Tt}^0) and rate of severity progress (τ_{Tt}). New fertilization practices could also impact the shape of the relative yield of symptomatic trees (φ^{ℓ}_{Tt}) and subsequent fruit grading ($\vartheta^{f}_{T}, \vartheta^{c}_{T}$).

Economic Module

The economic module assesses the economic feasibility of adopting different ACP and HLB management practices. We use projected revenues and production costs to evaluate and compare a set of financial indicators of each HLB control strategy evaluated.

Revenue and Cost of Production

The presence of HLB affects farmers' revenue by gradually reducing the yield potential. In addition, the overall quality of the fruit produced could also be altered by the disease and the control practices adopted. Total revenue in year T is given by

$$R_T = \begin{cases} \sum_g \left(p^g_T + \tilde{\varepsilon}^g_T\right) \tilde{\alpha}^g_T Y_T, & T < \Gamma + \tilde{\delta} \\ \sum_g \left(p^g_T + \tilde{\varepsilon}^g_T\right) Y^{Ig}_T, & T \geq \Gamma + \tilde{\delta} \end{cases}, \tag{21}$$

where $g = \{f, c, P\}$, p^g_T is the expected price received by growers for g-graded fruit, and $\tilde{\varepsilon}^g_T$ is the corresponding random price error term.

At the same time, the adoption of control practices aimed to reduce the spread and severity of the disease may increase production costs. Particularly, CLas-free certified trees are more expensive than their counterpart noncertified trees used before the occurrence of the disease. Also, a grove affected by HLB is expected to have a higher number of symptomatic trees and unproductive trees. Substantially higher replanting costs will be observed if an aggressive replanting strategy is adopted. Further, growers may opt for additional insecticide applications to maintain lower ACP populations levels. In some citrus production regions, a new citrus assessment fee has been implemented to fund coordinated area-wide monitoring and control strategies. Supplementary foliar fertilizer applications will also increase production costs. The total cost of production is represented as a function of the production practices adopted and their input prices:

$$C_T = \begin{cases} C'_T\left(\tilde{m}, \varrho, \boldsymbol{h}_T, \boldsymbol{d}_T, \boldsymbol{F}_T, \boldsymbol{u}_T\right) \tilde{\epsilon}_T, & T < \Lambda \\ C^I_T\left(\tilde{m}, \lambda_T, \varrho, \varrho^{IS}, \boldsymbol{h}_T, \boldsymbol{d}_T, \boldsymbol{F}_T, \boldsymbol{u}_T\right) \tilde{\epsilon}_T, & T \geq \Lambda \end{cases}, \tag{22}$$

where Λ is the year in which ACP and HLB control practices were initially adopted; $C'_T(\cdot)$ and $C^I_T(\cdot)$ are the expected total cost of production before and after adopting a HLB management plan, respectively; and $\tilde{\epsilon}_T$ is a stochastic cost variability factor. The cost function is a linear combination of the input prices and the corresponding input quantities used, where $\boldsymbol{h}_T$ is a vector of inputs and actions directed to control pest population levels (including ACP); $\boldsymbol{d}_T$ is an analogous vector of fertilizer applications; $\boldsymbol{F}_T$ represents all other production inputs independent of tree resetting, pest management, and fertilization decisions; $\boldsymbol{u}_T$ is a vector of input prices. The adoption of current ACP and HLB management programs is expected to change the removing and replanting rates ($\lambda_T, \varrho, \varrho^{IS}$), number of insecticide applications ($\boldsymbol{h}_T$), amount and quality of fertilizers used ($\boldsymbol{d}_T$), and the price of the new inputs used ($\boldsymbol{u}_T$).

Financial Indicators

We evaluate the economic feasibility of adopting various ACP and HLB management practices by comparing their net present value (NPV) or equivalent annual annuity (EAA). The NPV is defined as the sum of all expected net cash flows associated with a control strategy over a period of time, discounted to an equivalent present date (Remer and Nieto, 1995):

$$NPV = \sum_{T=\Psi}^{\Omega} \frac{(R_T - C_T)^*}{(1+i)^{T-\Psi}}, \tag{23}$$

where Ψ defines the beginning of the valuation period, Ω is the grove production termination year, i is the discount rate, and $(R_T - C_T)^*$ represents the cash flow adjusted by noncash expenses, capital expenditures, and financial obligations and liabilities. In general, the control strategy with the highest NPV is preferred over all other alternative management plans since it would be the most profitable option. The presence of HLB could reduce the economic life of an affected grove. Hence, we use the equivalent annual cost method to compare management programs with different lifespans $(\Omega - \Psi)$ (Jones and Smith, 1982). In this capital budgeting approach, an equivalent annual annuity (EAA) is estimated for each potential alternative:

$$EAA = \frac{i(NPV)}{1 - (1+i)^{-(\Omega-\Psi)}}. \tag{24}$$

As with NPV, the control strategy with the highest EAA is preferred.

Illustrative Application

The preceding stochastic model is exemplified in hypothetical HLB scenarios in Texas. This analysis should be viewed only as an illustration, and it is used to demonstrate the capabilities of the proposed evaluation framework. Around 350,000 tons of citrus were produced in Texas during the 2018–2019 growing season, with a market value of about $90 million, with grapefruit production accounting for 73% of sales (U.S. Department of Agriculture, 2020a). The presence of HLB was confirmed in Texas in 2012, and the disease has now become endemic in the state (Sétamou, da Graça, and Prewett, 2012; Sétamou et al., 2020). By 2017, HLB-positive trees were found in about 26% of all commercial blocks (Sétamou et al., 2020).

Two HLB incidence and management scenarios were evaluated. The first scenario considers a young, 5-year-old grapefruit grove, and the second evaluates a mature, 25-year-old grove. Each scenario analyzes three disease progression cases.[5] The first case represents the *ex ante* or baseline growing conditions, where no HLB incidence has occurred. In the second case, the initial HLB incidence occurred 5 (Scenario 1) and 25 years (Scenario 2) years after grove establishment, no HLB control practices were implemented, and the disease was allowed to progress freely. The third case follows the same incidence assumptions as case 2 but considers the AWM program recommendations described in Sétamou, da Graça, and Prewett (2012) and Sétamou et al. (2020) to limit the progress of HLB.

Data and Model Estimation

We used Monte Carlo simulation techniques to incorporate production and market uncertainty. Particularly, a total of 500 $\{EAA_{kj}, \boldsymbol{X}_j, \boldsymbol{Z}_k\}$ samples were generated for each of the three disease progression cases evaluated in each scenario, where EAA_{kj} is the equivalent annual annuity of the kth management plan under the production and market conditions of the jth iteration, $\boldsymbol{X}_j$ represents all model parameters independent of the HLB control strategy adopted and is the same for all disease progression cases within each scenario, and $\boldsymbol{Z}_k$ denotes the specific parameters related to the kth

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[5] Although the results are not presented, the economic feasibility of identifying and removing 85% of HLB symptomatic trees and subsequent replanting of CLas-free tress was also evaluated. Under this disease management practice, it was found that the younger grove became economically unviable 7 years after initial HLB incidence and the mature grove after 18 years.

management plan. In this hypothetical illustration, uniform and normal distribution functions within a reasonable range were assigned to particular parameters to model their underlying probability distribution functions. Appendix A describes the model parameters and corresponding distribution functions.

The analysis was performed on two 20-acre groves of "Rio Red" grapefruit (*Citrus* × *paradisi* Macfad.), which are of average size for a commercial citrus block in Texas (Arteaga, 2017). For illustration purposes, it was assumed that the groves were established in 2015 (Scenario 1) and 1995 (Scenario 2), with an initial planting density ($n'_{1,1}$) of 150 trees per acre and a maximum commercial lifespan (Ω') of 45 years.[6] Each grove began bearing commercial fruits 3 years after planting (A) and between 16 ton/ac to 20 ton/ac are expected to be harvested ($\tilde{y}_{\tilde{p}}$) at the peak of production ($\tilde{p}$). Proportional annual yield deviations ($\tilde{\imath}_t$) follow a zero-mean normal distribution with a standard deviation of 2.5%. Also, it was assumed that 0.5%–1.5% of established trees will succumb each year to abiotic and biotic factors other than HLB ($\tilde{m}$). Dead and unproductive trees are replaced by new, certified CLas-free trees at a rate equal to the mortality rate (ϱ). Given the delay in the entry into production of new planted trees and the expected remaining productive years of the grove, all tree resetting efforts are suspended when the grove reaches 35 years of age.

In terms of fruit quality, past state-level proportions of Texas Fancy, Texas Choice, and processed fruits were used to forecast yield grading. Particularly, the expected correlation between the proportions of fruits graded as Texas Fancy and Texas Choice was incorporated by drawing joint samples from a multinormal distribution with mean and covariance estimated using available historical data. On average over 2011–2018, 38.7% and 20.9% of the state's annual grapefruit production was graded as Texas Fancy ($\tilde{\alpha}^{f}_{T}$) and Texas Choice ($\tilde{\alpha}^{c}_{T}$), respectively.

For the no control (NC) and AWM cases, the first HLB incidence (Γ) in the grove occurred in 2019 for both scenarios, and trees began to show symptoms of the disease 2–3 years ($\tilde{\delta}$) after initial contact with the CLas bacterium. It is further assumed that 0.5%–1.5% of the existing trees were initially affected by HLB ($\tilde{N}^{I}_{\Gamma 0}$). Hereafter, HLB within the grove spreads at different rates depending on the management plan adopted. Particularly, in both scenarios, the AWM program was adopted the same year of initial HLB incidence (Λ) (i.e., 2019). Given the high adoption rates of AWM program in Texas, a modest and equal primary random infection rate ($\tilde{a}_{0,T}, \tilde{a}_{1,T}$) is considered in all cases with HLB incidence. Table 1 summarizes the parameter values for each scenario evaluated.

Regarding secondary HLB spread (μ_{Tt}), the HLB incidence growth rate observed in Texas (Sétamou et al., 2020) and the disease progress suggested by Bassanezi and Bassanezi (2008) were used as baseline.[7] The NC disease progression cases considered a two-fold secondary HLB growth rate compared to the rate used in their counterpart cases in which the AWM program was adopted. An additional 10% relative variability ($\tilde{\nu}_t$) was added to the secondary HLB growth rate to account for other external factors not considered in the model.

Similar to the HLB incidence, the discrete values suggested by Bassanezi and Bassanezi (2008) served as a baseline to estimate functional forms for the initial HLB severity level and severity progress rate without control interventions. It was assumed that the adoption of ACP control practices reduced annual severity by 50% and that young trees ($t \le \gamma$) are twice as likely to

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[6] The lifespan of a citrus grove depends on its care and its endurance to external events such as freezes (Anciso and Ribera, 2013). Groves older than 45 years might not be economically viable due to their reduced productivity and higher incidence of diseases (e.g., *Phytophthora*-induced foot rot).

[7] Sétamou et al. (2020) calculated a disease growth rate of 0.34 using a Gompertz function and based on a random sample consisting primarily of mature groves (i.e., 15 years or older). This annual rate of HLB incidence was used as a reference for trees older than 10 years and under the coverage of the AWM program. For younger trees, discrete growth rates were estimated proportionally to the rates proposed by Bassanezi and Bassanezi (2008). We approximated equivalent incidence growth rates to the logistic function by minimizing the sum of square errors between the expected incidence levels from the Gompertz curve and those computed by the logistic function in equation (4). We then compiled the discrete growth rates associated with the logistic function into a continuous function, where the logarithmic transformation was found to better fit the data among a series of alternative models based on the coefficient of determination criteria.

Table 1. Scenario Parameters

Parameter	Units	Symbol	Scenario 1	Scenario 2
Initial infection year	years	Γ	5	25
Initial adoption of ACP/HLB control practices	years	Λ	5	25
Expected secondary HLB growth rate	%	μ_{Tt}		
No control (NC) case			$\begin{cases} 6.48 - 2.48\ln(t)\ t \leq 10 \\ 0.98\ t > 10 \end{cases}$	
AWM case			$0.5 \times NC$	
Expected initial HLB severity level	%	$\bar{s}^0_{Tt}$		
No control (NC) case			$21.1 - 7.7\ln(t - \tilde{\delta})$	
AWM case			$0.5 \times NC$	
Expected HLB severity progress rate	%			
No control (NC) case			$3.85 - 1.38\ln(t)$	
AWM case			$0.5 \times NC$	
Insecticide applications	no. of times	h_T		
Ex ante			4	4
No control (NC) case			4	4
AWM case			6	6
Beginning of financial assessment	years	Ψ	5	25

become infected and therefore to present symptoms than mature trees.[8] Compared to Bassanezi and Bassanezi (2008), initial HLB severity is not a function of the current age of trees but of their age when got infected; thus, we considered the delay onset of symptoms. A 10% variability (ς_t,$\tilde{\zeta}_t$) was added to both the initial HLB severity level ($\bar{s}^0_{Tt}$) and severity progress rate ($\bar{\tau}_{Tt}$) since there is not a clear consensus on the variability of these parameters.

We assumed a minimal effect on yield at lower HLB severity levels. Noticeable reductions in yield begin when HLB severity reaches about 20%. The parameters of equation (16) related to the origin (Q) and inflection point (v) of the relative yield loss curve are set to accomplish the

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[8] The relative symptomatic propensity decreases as more trees became symptomatic. Namely,

$$\eta_T = \begin{cases} 2\beta_T,\ \Delta N_T^{IS} \leq \min\left(L_T^1, L_T^2\right) \\ 1,\ L_T^1 < \Delta N_T^{IS} \leq L_T^2 \\ \dfrac{\Delta N_T^{IS} - (1-\tilde{m}) \sum_{t=\gamma+1}^{T} \left(n_{T-1,t-1} - \sum_{\ell=1}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right)}{(1-\tilde{m}) \sum_{t=\tilde{\delta}+1}^{\gamma} \left(n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right)},\ L_T^2 < \Delta N_T^{IS} \leq L_T^1 \end{cases},$$

where

$$L_T^1 = (1-\tilde{m}) \left[\sum_{t=\tilde{\delta}+1}^{\gamma} \left(n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right) + 0.5 \sum_{t=\gamma+1}^{T} \left(n_{T-1,t-1} - \sum_{\ell=1}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right)\right],$$

$$L_T^2 = (1-\tilde{m}) \left[2 \sum_{t=\tilde{\delta}+1}^{\gamma} \left(n_{T-1,t-1} - \sum_{\substack{\ell=1 \\ t-1>\tilde{\delta}}}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right) + \sum_{t=\gamma+1}^{T} \left(n_{T-1,t-1} - \sum_{\ell=1}^{t-1-\tilde{\delta}} n_{T-1,t-1}^{\ell}\right)\right],$$

and $\min\left(L_T^1, L_T^2\right)$ represents the maximum possible number of symptomatic prone trees for the expected distribution of new symptomatic trees between young and mature trees (i.e., $\eta_T/\beta_T = 2$) to hold. Accordingly, β_T values are calculated by solving equation (9).

expected delay of the negative effect of severity on yield. The random yield loss growth rate ($\tilde{B}$) and asymptotical minimum relative yield ($\tilde{K}$) encompass the observed variability reported by Bassanezi et al. (2011). The effect of HLB on fruit quality is projected to follow a trend similar to that of the relative yield loss curve. The proportion of premium fruit is expected to be more sensitive to the evolution of HLB compared to lower quality grades. Maximum losses in fruit quality attributed to the progress of the disease were set to mean values of 20% and 15% for fruits graded as Texas Fancy ($\tilde{K}^f$) and Texas Choice ($\tilde{K}^c$), respectively. Likewise, a relatively slower rate of fruit quality loss was used for Texas Choice ($\tilde{B}^c$) than for Texas Fancy ($\tilde{B}^f$).

Linear regression models were fitted to calculate the expected price trend[9] for fruits graded as Texas Fancy (p_T^f) and Texas Choice (p_T^c). In the case of processed fruit, the average price for processed grapefruit in Texas in marketing years 2007–2013 served as expected baseline (p_T^P) due to the limited data to estimate a price trend (U.S. Department of Agriculture, 2020a). Random price errors ($\tilde{\varepsilon}_T^f$, $\tilde{\varepsilon}_T^c$, $\tilde{\varepsilon}_T^P$) drawn from a multivariate normal distribution with covariance matrix estimated using available data were added to the expected price trends.

Production costs were based on the Texas A&M AgriLife Extension Service (2019) grapefruit enterprise budgets for groves at least 5 years old. Before implementing the AWM management plan, the annual cost of production (C_T') was estimated at $1,433/acre plus variable plant resetting expenses, interests on operating capital, and depreciation. The *ex ante* baseline cost consists of all fertilizer, insecticide, herbicide, pruning and trimming, irrigation, and other miscellaneous expenses. Due to a well-developed root system, mature trees are more expensive than to young trees to remove completely. Additionally, the overall establishment and maintenance costs incurred during the first 3 years after the initial setup of the grove were proportionately allocated to the following 10 productive years' cash flows as added depreciation costs. The *ex ante* cost structure was used for the baseline and no HLB control cases for both scenarios. When AWM recommendations are followed, two additional custom insecticide applications are conducted, representing an overall increase in insecticide costs of $108.85/acre ($C_T^I$). Production costs were projected by multiplying the expected costs (based on 2019 input prices) by the forecasted Prices Paid Index for Commodities and Services, Interest, Taxes, and Farm Wage Rates ($\tilde{\epsilon}_T$) (U.S. Department of Agriculture, 2019a).

Last, tax liabilities assumed a 21% income tax rate, deducted from the gross cash flows. Depreciation was added back to the after-tax income to estimate the net cash flows used in the NPV analysis. A discount rate (i) of 7.5% was used in the economic feasibility assessment, which started 5 and 25 years after initial planting (Ψ) for the young and mature grove scenarios, respectively. HLB management plans were evaluated through the productive lifetime of the grove (i.e., 45 years); however, early termination was considered after 3 consecutive years of negative net cash flows. At termination, the grove is no longer economically viable, so we assume that it would be replaced by a new plantation; therefore, the residual value of the standing trees is equal to 0.

Illustration Results

We evaluated the economic feasibility of implementing an AWM program in young and mature Texas grapefruit groves under comparable HLB incidence levels. In the young grove (Scenario 1) when no control actions are taken, HLB incidence progressed at a faster pace, reaching the asymptotic maximum 7 years after the first incidence (Figure 2). When the AWM program is adopted, the highest HLB incidence levels occurred 25 years after the initial incidence. At the end of its production cycle under the no-control case (i.e., 18 years), the HLB incidence rate on the young grove was 98.13% compared to 93.92% observed at the same time under the AWM case. Relative

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[9] Grapefruit shipping prices associated with the Lower Rio Grande Valley in Texas were aggregated by year and grade and then adjusted by the corresponding harvesting, packing, and grading costs (U.S. Department of Agriculture, 2020b). Costs incurred at harvest and through the packinghouse were inferred from the annual differential between the Texas grapefruit FOB (free on board) and on-tree equivalent fresh market prices in U.S. Department of Agriculture (2020a). Missing values were imputed by using the mean proportional packing and grading cost.

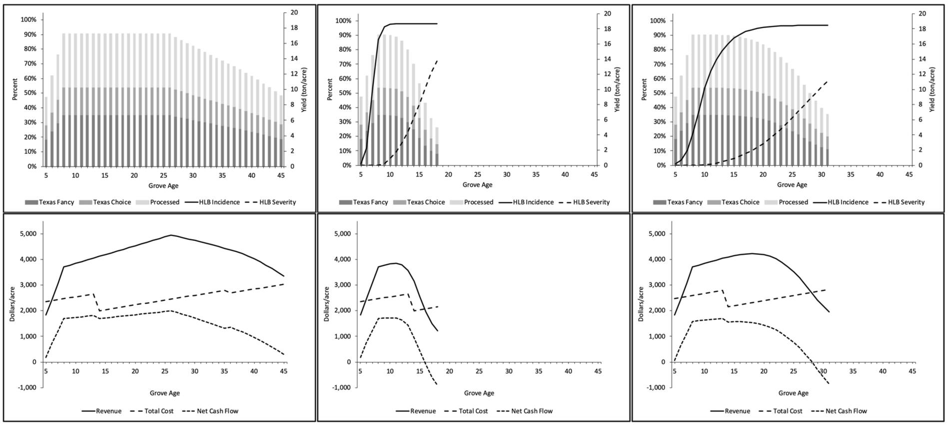

Figure 2. Expected HLB Incidence, HLB Severity, Yield (top), Revenue, Total Cost, and Net Cash Flow (bottom) of Baseline (left), No Control (middle), and Area-Wide Management (AWM) (right) Case in a 5-Year-Old Grove

Notes: Random variables were evaluated at their expected value.

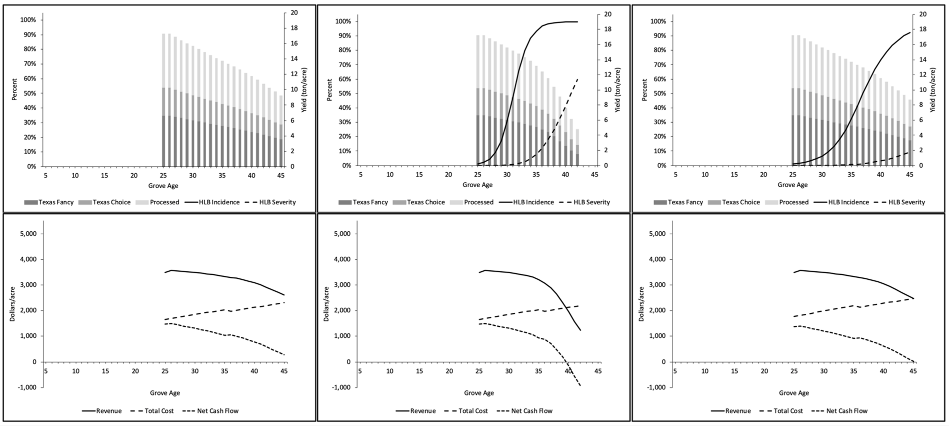

Figure 3. Expected HLB Incidence, HLB Severity, Yield (top), Revenue, Total Cost, and Net Cash Flow (bottom) of Baseline (left), No Control (middle), and Area-Wide Management (AWM) (right) Case in a 25-Year-Old Grove

Notes: Random variables were evaluated at their expected value.

slower HLB incidence growths were observed in the mature grove (Scenario 2) under both the NC and AWM cases. Specifically, the asymptotic HLB incidence rate (i.e., 99.92%) was reached 18 years after initial incidence in the NC case, and a 92.36% incidence was recorded at the end of the grove's life (21 years after first incidence) when the AWM program was implemented (Figure 3).

In terms of HLB severity, a faster severity progression was also observed under the NC case in both scenarios. Particularly, final aggregated severity levels equal to 72.06% and 58.39%, respectively, were estimated without control actions and under the AWM program in the young grove. In Scenario 2, overall severity levels of 59.71% and 9.30% were observed at the end of the production lifespan in the NC and AWM cases, respectively. Model results suggest that the negative effects caused by the progression of HLB severity could be hampered by the timely implementation of effective management practices.

Significant differences in yields were also observed among the scenarios. Compared to the baseline case, the occurrence of HLB reduced the productivity of the grove irrespective of the control measures taken. As HLB severity progressed, so did the detrimental effects on yield and fruit quality.

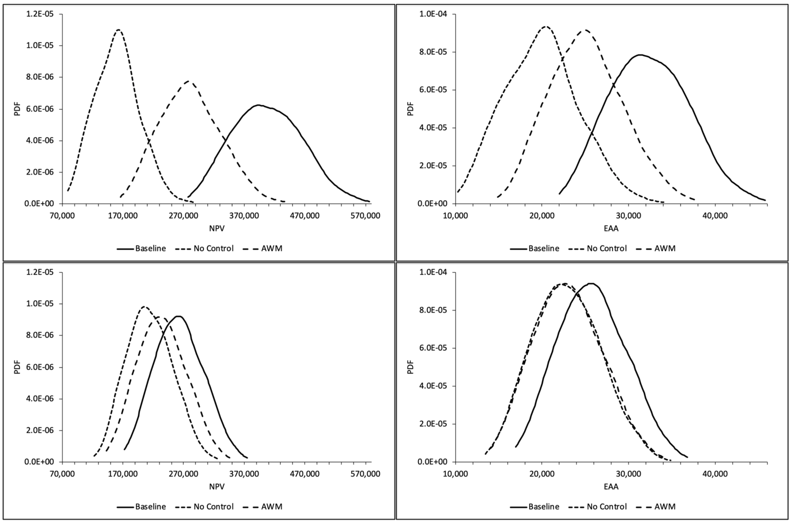

Figure 4. Probability Density Function (PDF) of the Net Present Value (NPV) and Equivalent Annual Annuity (EAA) for the Young Grove (top) and Mature Grove (bottom) Scenarios

For instance, in the young grove scenario, total yield decreased from a potential 17.22 ton/acre in year 18 to 4.98 ton/acre in the NC case and from 15.23 ton/acre in year 31 to 6.72 ton/acre in the AWM case. Compared to the baseline case, at the peak of severity 7.41% and 6.82% less of overall production was graded as Texas Fancy under the NC and AWM cases, respectively. Similar yield and quality loss patterns were estimated when the grove was infected at a mature stage.

The presence of HLB resulted in a substantial decrease in revenues, particularly when no control actions were adopted. Revenue losses were accelerated as the disease severity adversely affected yield and fruit quality. Likewise, production costs increased with the implementation of the AWM management strategy. In Scenario 1, net cash flows became negative 12 years after initial HLB incidence when no control actions were adopted and 25 years after initial infection when the AWM program was in place. In the mature grove scenario, when no actions were taken to mitigate the progress of the disease, keeping the grove in production for more than 15 years after first HLB incidence was no longer economically viable. By adopting the AWM program, production could be extended for 21 more years. Based on the termination criteria, the AWM case in Scenario 2 was the only instance in which the productive lifecycle of the grove extended to 45 years, suggesting that the presence of HLB could drastically reduce the expected economically productive life of a grove.

Figure 4 presents the estimated probability distribution function of the NPV and EAA for each of the scenarios evaluated. Although not comparable given the different lifespans of groves under different disease management strategies, the distribution of the NPVs demonstrates the potential economic risk and value of each HLB management plan in a 20-acre grapefruit grove as well as the latent economic burden imposed by the disease. The expected NPV associated with the baseline production conditions without HLB incidence was $408,087 and $262,862 for Scenarios 1 and 2, respectively. In the young grove case, the mean NPV decreased to $160,582 when no control actions were taken and to $280,819 when the AWM program was implemented. A relatively lower reduction in NPV was observed in the mature grove scenario: Expected NPV was $214,379 for the NC case and $234,242 when the AWM program was followed.

Under the assumptions of the simulation application and based on the EAA discrimination criteria for projects with different duration, the AWM program was preferred over the NC alternative in both scenarios evaluated, particularly in the case of the young grove, where the mean EAA of adopting the AWM program was $25,092 compared to $19,952 when no control actions were implemented. A slightly higher EAA ($22,982) was obtained in the mature grove scenario under the

AWM program relative to the NC case ($22,831). As in the NPV results, a substantial drop in value was observed in all HLB-related cases compared to the baseline conditions. The corresponding EAA of the baseline case was $32,402 and $25,785 in the young and mature grove scenarios, respectively.

Summary and Conclusions

This paper presented a systematic evaluation framework to assess the economic feasibility of potential control strategies for mitigating the devastating effects of huanglongbing (HLB) on citrus production. The proposed model is based on flexible functional forms to represent the intricate relationships between HLB epidemiology, effectiveness of management practices, and economic implications. Unlike existing economic studies, we developed a fully traceable evaluation framework in which fixed ad hoc assumptions about the effect of intervention actions on the progress of the disease were relaxed by adopting a sequential iterative approach. This approach allowed us to evaluate the long-term economic feasibility of a broad range of current and prospective Asian citrus psyllid (ACP) and HLB management alternatives. We applied the model to simulate grapefruit production in Texas, evaluating two alternative management strategies under comparable HLB incidence levels in a young and a mature grove. The simulation results highlighted the detrimental effects of the disease and the importance of developing cost-effective control options. Based on the production, market, and HLB epidemiology scenarios considered, adopting an effective area-wide ACP control strategy was preferred over the no control alternative. A substantial loss in value is expected in an infected grove regardless of the HLB control plan implemented.

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Table A1. Model Parameter Values and Distributions

Parameter	Symbol	Units	Value	Distribution	Reference
Initial planting density	$n'_{1,1}$	trees/acre	150		Wiedenfeld and Sauls (2008), Sauls (2008), Texas A&M AgriLife Extension Service (2019)
Maximum lifespan	Ω'	years	45		Gottwald, Aubert, and Zhao (2010), anecdotal evidence
Beginning of production	A	years	3		Sauls (2008)
Initial pick of production	$\tilde{p}$	years		Discrete uniform (7, 9)	Sauls (2008)
Initial decline of production	$\tilde{d}$	years		Discrete uniform (25, 30)	Sauls (2008), anecdotal evidence
Initial commercial yield	$\tilde{y}_{\mathrm{A}}$	ton/acre		Uniform (3, 4)	Sauls (2008)
Pick of production yield	$\tilde{y}_{\tilde{p}}$	ton/acre		Uniform (16, 20)	Wiedenfeld and Sauls (2008), Sauls (2008), anecdotal evidence
Final commercial yield	$\tilde{y}_{\Omega'}$	ton/acre		Uniform (7, 9)	Anecdotal evidence
Random yield variability factor	$\tilde{l}_t$	%		N (0, 6.25)	Anecdotal evidence
Non-HLB mortality rate	$\tilde{m}$	%		Uniform (0.5, 1.5)	Futch, Graham, and Duncan (2008), Texas A&M AgriLife Extension Service (2019), anecdotal evidence
Non-HLB replanting rate	ϱ	%	$\begin{cases} 100 & T < 35 \\ 0 & T \geq 35 \end{cases}$		Anecdotal evidence
Baseline proportion of Texas Fancy	$\tilde{\alpha}^f_T$	%		$N\left(\begin{bmatrix} 38.7 \\ 20.9 \end{bmatrix}, \begin{bmatrix} 9.0 & -14.9 \\ 29.3 & \end{bmatrix}\right)$	Texas Valley Citrus Committee (2018)
Baseline proportion of Texas Choice	$\tilde{\alpha}^c_T$	%			
Initial infection year	Γ	years			
Scenario 1			5		
Scenario 2			20		

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Table A1. continued from previous page

Parameter	Symbol	Units	Value	Distribution	Reference
Delayed onset of HLB symptoms	$\tilde{\delta}$	years		Discrete uniform (2, 3)	Gottwald, Aubert, and Zhao (2010)
Initial HLB affected trees	$\tilde{N}^{I}_{\Gamma^0}$	trees/acre		N_T×Uniform (0.005, 0.015)	Bassanezi and Bassanezi (2008), Sétamou, da Graça, and Prewett (2012)
Initial adoption of ACP/HLB control practices	Λ	years			
Scenario 1 – AWM			5		
Scenario 2 – AWM			20		
Primary HLB incidence growth rate components	$\tilde{a}_{0,T}$	%/year		Uniform (0, 5)	Gottwald, Aubert, and Zhao (2010)
	$\tilde{a}_{1,T}$	%/year		Uniform (0, 5)	
Expected secondary HLB growth rate	μ_{Tt}	year^{-1}			Bassanezi and Bassanezi (2008), Sétamou et al. (2020)
No control (NC) case			$\begin{cases} 6.48 - 2.48\ln(t) & t \leq 10 \\ 0.98 & t > 10 \end{cases}$		
AWM case			$0.5 \times NC$		
Secondary HLB growth rate variability factor	$\tilde{\nu}_t$	%		Uniform (−10, 10)	Gottwald, Aubert, and Zhao (2010)
Young trees	γ	years	10		Bassanezi and Bassanezi (2008)
Expected initial HLB severity level	$\bar{s}^{0}_{Tt}$	%			Bassanezi and Bassanezi (2008)
No control (NC) case			$21.1 - 7.7\ln(t - \tilde{\delta})$		
AWM case			$0.5 \times NC$		
Initial HLB severity level variability factor	$\tilde{\varsigma}_t$	%		Uniform (−10, 10)	

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Parameter	Symbol	Units	Value	Distribution	Reference
Expected HLB severity progress rate	$\bar{\tau}_{Tt}$	year-1			Bassanezi and Bassanezi (2008)
No control (NC) case			$3.85 - 1.38\ln(t)$		
AWM case			$0.5 \times NC$		
HLB severity progress rate variability factor	$\tilde{\zeta}_t$	%		Uniform (−10, 10)	
Effect on origin of the relative yield loss curve	Q		1.5		Anecdotal evidence
Effect on inflection point of the relative yield loss curve	ν		0.11		Anecdotal evidence
Yield loss growth rate	$\tilde{B}$	%/year		Uniform (6, 7)	Bassanezi et al. (2011)
Asymptotic relative yield loss	$\tilde{K}$	%		Uniform (14, 19)	Bassanezi et al. (2011)
Growth rate of Texas Fancy relative change	$\tilde{B}^f$	%/year		Uniform (7.5, 8.5)	Anecdotal evidence
Asymptotic Texas Fancy relative change	$\tilde{K}^f$	%		Uniform (78, 82)	Anecdotal evidence
Growth rate of Texas Choice relative change	$\tilde{B}^c$	%/year		Uniform (6.5, 7.5)	Anecdotal evidence
Asymptotic Texas Choice relative change	$\tilde{K}^c$	%		Uniform (83, 87)	Anecdotal evidence
Texas Fancy price	p_T^f	$/ton	$363.52 + 3.06T$		U.S. Department of Agriculture (2020a,b)
Texas Choice price	p_T^c	$/ton	$271.06 + 8.69T$		U.S. Department of Agriculture (2020a,b)
Processed fruit price	p_T^P	$/ton	5.40		U.S. Department of Agriculture (2020a)

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Parameter	Symbol	Units	Value	Distribution	Reference
Texas Fancy price error	$\tilde{\varepsilon}_T^f$	$(\$/ton)^2$		$N\left(\mathbf{0}, \begin{bmatrix} 2,664.9 & 439.0 & 41.5 \\ & 572.6 & 167.2 \\ & & 94.3 \end{bmatrix}\right)$	U.S. Department of Agriculture (2020a,b)
Texas Choice price error	$\tilde{\varepsilon}_T^c$	$(\$/ton)^2$			
Processed fruit price error	$\tilde{\varepsilon}_T^P$	$(\$/ton)^2$			
Ex ante cost of production	C'_T	\$/acre			Texas A&M AgriLife Extension Service (2019)
Baseline cost		\$/acre	1,433.09		
Tree planting		\$/tree	17		
Tree removal		\$/tree	$\begin{cases} 7 & t \leq 3 \\ 30 & t > 3 \end{cases}$		
Interest rate		%	5		
Machinery depreciation		\$/acre	16.65		
Establishment depreciation		\$/acre	$\sum_{T=1}^{3} \frac{C'_T}{10} \ \forall\, 4 \leq T < 14$		
Ex post cost of production	C_T^I	\$/acre			Texas A&M AgriLife Extension Service (2019)
Baseline cost		\$/acre	C'_T		
AWM-related insecticide applications		\$/acre	108.85		
Cost variability factor	$\tilde{\epsilon}_T$	%		$N(92.75 + 2.36T, 33.47)$	U.S. Department of Agriculture (2019a)
Beginning of financial assessment	Ψ	years			
No control (NC) case			5		
AWM case			20		
Discount rate	i	%	7.5		Trejo-Pech, Spreen, and Zansler (2018)