Citrus Greening: Management Strategies and Their Economic Impact

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Abstract. Citrus huanglongbing (HLB), or greening, is the most destructive citrus disease worldwide and is threatening the sustainability of the industry in major citrus-growing regions. Various treatments have been proposed in the literature to manage the disease. We review such literature and conduct an economic analysis based on the reported treatment effects on fruit yield and quality to identify cost-effective management strategies. Our results suggest that, among the treatments we reviewed, broad-spectrum insecticides provide the only cost-effective strategy for mitigating the impact of the disease. Our findings and discussion should help growers, policymakers, and other stakeholders make informed decisions in the search for effective, sustainable, and environmentally friendly treatments and policies against HLB.

Citrus is one of the top specialty crops grown in the United States. It ranks third in terms of bearing area (after almonds and grapes) and accounts for 16% of the total value of U.S. fruit production. On the demand side, citrus juice is the major fruit drink nationwide, accounting for nearly half of the domestic fruit juice market (USDA-ERS, 2018). During the 2016–17 season, the U.S. citrus industry contributed to the nation's economy by generating over \$15 billion and over 70,000 jobs. In recent years, however, the U.S. citrus industry has suffered major production losses due to citrus huanglongbing (HLB), or greening disease. The disease is caused by the bacterium *Candidatus Liberibacter asiaticus* (CLAs), and it is transmitted by an insect vector [Asian citrus psyllid (ACP), *Diaphorina citri*] in the United States. The disease can cause a significant reduction in fruit quality and severely

debilitate citrus trees, resulting in a significant yield loss (Iftikhar et al., 2016). Trees affected by HLB can become unproductive within 2 to 5 years and their lifespan can be reduced from 50 years to 7–10 years (Ehsani et al., 2016; Jia et al., 2017). Thus, HLB has become the greatest challenge for U.S. citrus growers and the industry, particularly in Florida (Singerman and Rogers, 2020).

Florida is the largest orange producer in the United States, and over 90% of its crop is processed into juice. Florida is the state that has been impacted the most by HLB. The estimated damage of the disease over the past 5 years amounts to over \$1 billion per year, with nearly 5000 jobs lost annually. Grove-bearing area in Florida has declined by 30% since the outbreak of the disease in 2005, along with a 74% decline in production (Fig. 1) (Court et al., 2017). It is estimated that 90% of the acreage and 80% of citrus trees in Florida are affected by the disease (Singerman and Useche, 2017).

Due to the impact of HLB in Florida, since the 2016–17 season, California has become the largest citrus producer in the United States. California produces over 80% of the nation's fresh oranges despite HLB being discovered in California in 2012. Since then, many counties have been infested

with ACP, including San Diego, Imperial, Riverside, San Bernardino, Orange, Los Angeles, Santa Barbara, and Ventura. Host plants infected with HLB and/or ACP have been found to be positive for CLAs in Los Angeles, Orange, San Bernardino, and Riverside counties. Lopez and Durborow (2015) estimated that even if California aggressively combats HLB, the economic loss will still be \$2.2 billion over the next 20 years. Currently, a voluntary area-wide pest management program is in place, and the California Department of Food and Agriculture has implemented an action plan to manage ACP and HLB. The plan includes an eradication program of diseased trees, the use of pesticide applications and biological control, a state-wide early detection program, and a regulatory program for ACP and HLB.

Most commercial cultivated citrus varieties are susceptible to CLAs infection. And, despite significant scientific research efforts, there is yet no cure for HLB in commercial settings. Some of the strategies proposed for vector control and disease treatment include chemotherapy (Zhang et al., 2014), foliar sprays (Spann et al., 2011), chemotherapy (Hoffman et al., 2013), biological control (Alvarez et al., 2016; Cazorla and Mercado-Blanco, 2016), and tree replacement (Gottwald, 2010; Martini et al., 2015). Some scientists are looking into using transgenic citrus to cope with the disease, but this approach faces both biological and economic challenges. Transgenics have a high cost of development and would require planting new trees.

Some previous studies have reviewed the effects of management strategies against HLB, including chemical control (Blaustein et al., 2018), insecticides (Boina and Bloomquist, 2015), nutritionals (Xia et al., 2011), biological control (Grafton-Cardwell et al., 2013), and other treatments (Munir et al., 2017). However, those studies focused on the comparison of different practices within one strategy and their effects on controlling ACP, reducing/preventing HLB incidence, and on yield. A comprehensive analysis of the costs and benefits of those strategies and a cross comparison among them have never been conducted. Thus, the aim of this article is 2-fold. First, to provide an overview of the HLB management strategies proposed in the literature with an emphasis on their effects on crop yield, costs, and benefits. Second, to assess the economic impact of the major proposed treatments to cope with the disease and analyze their cost-effectiveness. In the next section, we review management practices for HLB control, and in the following section we present the analysis of their economic performance. The final section presents major findings and recommendations.

Management Practices for HLB Control

In this section, we review the literature on HLB management practices, focusing on the economic impact of major treatments to cope with the disease, including antibiotics,

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Fig. 1. Changes on bearing acreage and production in Florida and California.

insecticide applications, enhanced foliar nutritional programs, thermotherapy, and biological control. The cost-effectiveness of each type of treatment is estimated by computing the difference between associated benefits and costs. For our calculations, we assume tree density to be 134 trees per acre, which is the average grove density in Florida according to data from the U.S. Department of Agriculture—National Agricultural Statistics Service (USDA–NASS). In addition, we set the 2016–17 season as our baseline because it is the most recent year for which final estimates are available with no extreme weather events (i.e., hurricanes). In that season, the average yield per tree was 1.37 boxes, and the on-tree price was \$11.82 per box. For each treatment that we analyze, we compute the yield change in percentage terms relative to the control group reported in the literature. The associated benefits (revenue) of treatments are calculated by multiplying the yield change from proposed treatments by the orange on-tree price. The cost of the treatment includes material cost (if applicable) and application cost (labor, equipment, etc.). The profit and benefit-cost ratio (BCR) for each treatment are calculated by subtracting costs from benefits and by dividing benefits by costs, respectively.

HLB control with antibiotics. The effectiveness of using antibiotics to cope with

plant diseases has been under debate for decades. The widespread use of antibiotics is controversial due to public concerns regarding their potential negative effects on human health and the development of antibiotic-resistant bacteria (Aćimović et al., 2015; Stockwell and Duffy, 2012). Moreover, even though some antibiotic treatments have been found to be biologically effective to control plant diseases, they had to be abandoned partly due to their prohibitive costs in the field. Such was the case for the use of tetracycline in the 1970s, which seemed to be a promising treatment but was later discontinued due to both phytotoxicity and high costs (Aldeek et al., 2015, 2016). Streptomycin and oxytetracycline (OTC) have also been used in the United States for over 50 years, but their use has been restricted to only a few bacterial plant diseases due to their high cost and the development of antibiotic resistance (Blaustein et al., 2018; Sundin and Wang, 2018).

Studies have documented the response of HLB-affected trees to antibiotics when using different application methods, namely, foliar sprays, root drench, and trunk injections (Puttamuk et al., 2014; Zhang et al., 2011, 2012, 2013). Trunk injections of antibiotics have been found to have a higher efficacy compared with soil drenching and foliar sprays (Zhang et al., 2011). However, the

costs associated with trunk injections may restrict their use on a large scale. Dixon et al. (2014) showed that the total cost of the injection of antibiotics was about \$5 per tree (i.e., \$1 for antibiotics, \$1.50 for injection devices, and \$2.50 for labor and other). Using data collected from growers (Singerman, 2019), we estimate the application cost for foliar sprays to be \$180 per acre (six applications per season at \$30 per application). Following application recommendations from scientists at the University of Florida Citrus Research and Education Center, the associated cost of materials (i.e., antibiotics) is estimated to range between \$110 and \$165, depending on the citrus variety.

In Table 1, we summarize the results of the studies that have reported changes in citrus yield of treated trees using antibiotics through field trials and greenhouse experiments. Shokrollah et al. (2011) conducted grouped treatments on infected citrus in Malaysia and found that injecting antibiotics + GA₃ was the most effective treatment (with a 231% higher fruit yield relative to untreated trees). Hu and Wang (2016) found a lower yield increase (15% on average) in OTC treatment experiments in Florida using trunk injection with varying numbers of injection ports. Hu et al. (2017) found a significant yield increase in sweet orange trees and better fruit quality by applying eight plant

Table 1. Impact of antibiotics and plant defenses on fruit yield and profit.

Treatment	Impact on yield ^z	Cost (\$) ^y	Benefit (\$) ^x	BCR ^w	Location	Reference
Oxytetracycline hydrochloride (OTC) (trunk injection)	Much higher fruit weight than untreated trees	—	—	—	Malaysia, 2008	Shokrollah et al. (2011)
	Average yield increased by 15%	609	397	0.65	FL, 2015–16	Hu and Wang (2016)
	Yield increased by 38% to 52%	505–587	943–1284	1.87–2.19	FL, 2014–16	Hu et al. (2017)
Penicillin (trunk injection)	50% to 60% increase in yield	550–560	1240–1676	2.2–3.5	FL, 2014–16	Hu et al. (2017)
Streptomycin sulfate	44% to 47% increase in yield	552–575	1070–1141	1.9–2.0	FL, 2014–16	Hu et al. (2017)
β-aminobutyric acid	Yield increased by less than 3%	618	67	0.1	FL, 2014–16	Hu et al. (2017)
	12% to 40% increase in yield	540–590	308–870	0.5–1.4	FL, 2013–14	Li et al. (2015)
INA	Yield increased by nearly 10%	586	235	0.4	FL, 2014–16	Hu et al. (2017)
	Yield increased by nearly 2% to 40%	548–630	52–210	0.1–0.3	FL, 2013–14	Li et al. (2015)
Others (i.e., BTH, DDG)	Yield changed from –6% to 28%	513–616	–135–678	–0.24–1.17	FL, 2014–16	Hu et al. (2017)
	Yield changed from –6% to 31%	502–649	–151–720	–0.28–1.01	FL, 2013–14	Li et al. (2015)

^zThe results are calculated based on data in the existing studies.^yCosts include materials and labor and are adjusted by annual tree density.^xPrices used in calculating benefits are the annual average on-tree price from USDA–NASS.^wBCR denotes Benefit-to-Cost Ratio.

Table 2. Impact of using insecticides on fruit yield and profit.

Treatment	Impact on yield ^z	Cost (\$) ^y	Benefit (\$) ^x	BCR ^w	Location	Reference
7 insecticides	Increased by 4 kg per tree, and yield changed from –10% to 17%	279	–301–435	–1.1–1.6	FL, 2012	Stansly and Roka (2013)
10+ insecticides	Yield changed from –3.7% to 29%	99–278	–110–830	–1.1–5.9	FL, 2008–12	Stansly et al. (2014)
10+ insecticides	Increase by \$335 to \$1613 per acre	293–556	355–1613	1.2–2.9	FL, 2011	Monzó and Stansly (2015)
13 insecticides	Increase by 13% to 38%	124–403	284–961	1.2–3.3	FL, 2012–16	Tansey et al. (2017)
Over 30 insecticides	Yield changed from –27% to 53%	29–717	–602–1292	–3.9–6.2	FL, 2010–14	Monzó and Stansly (2017)
20 insecticides	—	97–404	—	—	Brazil, 2004–05	Belasque et al. (2010)
Pesticide applications	—	283–485	—	—	CA, 2008	Lopez and Durborow (2015)

^zThe results are calculated based on data in the existing studies.^yCosts include materials and labor and are adjusted by annual tree density.^xPrices used in calculating benefits are the annual average on-tree price from USDA–NASS.^wBCR denotes Benefit-to-Cost Ratio.

activators: SA, oxalic acid, potassium phosphate dibasic, ASM, imidacloprid, L-ascorbic acid sodium salt, β-aminobutyric acid, and 2,6-dichloro-isonicotinic acid (INA), and three antibiotics, including oxytetracycline hydrochloride (OTC), penicillin G sodium salt (PCN), and streptomycin sulfate salt (STM) via trunk injection.

Based on those reported treatment effects, in Table 1 we also show the costs and benefits of the different antibiotic treatments using the application costs described above and the annual average on-tree prices from the USDA–NASS. While penicillin, oxytetracycline, and streptomycin sulfate increase profits by \$339–\$664 per acre, those compounds (particularly when applied using trunk injections) can leave a level of residue in the fruit that poses a risk for human consumption. Penicillin, in particular, which has been found to inhibit the growth of sensitive bacteria by inactivating enzymes located in the bacterial cell membrane (Yang et al., 2015; Zhang et al., 2010, 2014), is unlikely to be approved for use in citrus groves due to its potential impact on human health and the risk that would entail the development of resistant bacteria. The spraying of plant defense regulators (i.e., ascorbic acid, β-aminobutyric acid, INA, etc.) results in negative profits compared with the untreated control because the increase in revenue is not enough to cover the cost of the treatment.

In 2016, streptomycin sulfate, oxytetracycline hydrochloride, and oxytetracycline

calcium complex were approved for use as foliar sprays to treat HLB in Florida (Blaustein et al., 2018) despite the lack of evidence of such application methods being effective in the field; scientific findings that streptomycin and oxytetracycline provided control against HLB were from experiments conducted either in a laboratory setting (Zhang et al., 2014) or using trunk injections (Hu and Wang, 2016). In fact, it has been found that foliar sprays have no positive effect on yield in the field (Li et al., 2019).

Recent studies have suggested that antimicrobial peptides (AMPs) are beneficial in controlling HLB, but their use in the field has been delayed due to their high cost (Guerra-Lupián et al., 2018; Velasquez Guzman et al., 2018). Choi et al. (2017) proposed that small, synthetic AMPs (usually less than ten amino acids) could be a good alternative because their cost is much lower than that of native AMPs; but this needs further research (Choi et al., 2017).

Insecticides application. Broad-spectrum insecticides have proven to be an effective strategy for reducing ACP populations, especially when targeting overwintering adult populations during tree dormancy (Qureshi and Stansly, 2010). Systemic neonicotinoid insecticides, thiamethoxam, imidacloprid, and clothianidin, as well as cyantraniliprole, are allowed to be used in Florida citrus production (Boina and Bloomquist, 2015) but have some restrictions for their use on young trees (Qureshi et al., 2011, 2014).

Stansly and Roka (2013) reported that after having applied seven insecticides on Valencia orange trees in Florida to control the ACP, the average yield increased by 4 kg per tree from 2009 to 2012, with an associated cost of \$279 per acre. Stansly et al. (2014) conducted a 4-year field study and found that the average yield of oranges was 50 kg per tree with the insecticide treatment compared with 44 kg per tree without it. The cost associated with the insecticide applications was about \$99–\$278 per acre. Monzó and Stansly (2015) showed that insecticide treatments targeting ACP in citrus orchards led to higher revenue (about \$985 per acre) and costs (up to \$424 per acre). Similarly, Tansey et al. (2017) applied 13 different insecticides and found that the average yield in the treatment group was 80 kg per tree, which was 20% (13 kg per tree) higher than yield in the untreated group (67 kg); they reported that the associated cost for insecticide applications was about \$254 per acre. Monzó and Stansly (2017) tested 30 insecticides and found the yield improvement was insignificant (42-kg solids per acre on average), but that cost could increase by \$607 per acre. Studies beyond Florida also showed similar results in terms of the cost of using insecticides. For example, in Brazil, the cost was estimated at \$97–\$404 per acre (Belasque et al., 2010) and in California, \$283–\$485 per acre (Lopez and Durborow, 2015).

Table 2 presents the impact of using insecticides for HLB control based on the results reported in the cited studies. The yield

change ranged from -27% to 53%, resulting in revenue ranging from -\$602 to \$1292 per acre when using the USDA-NASS annual average on-tree price, while the cost ranged from \$29 to \$717 per acre. Overall, the BCR of using insecticides across studies is from -3.9 to 6.2.

While the use of insecticides has been shown to have a significant impact on citrus fruit yield when psyllid infestation rates are high, intensive insecticide use can result in resistance in ACP populations and also can increase the probability of secondary pest outbreaks (Tansey et al., 2017). For instance, Chen et al. (2018) reported the evidence of psyllid field populations showing moderate to high levels of resistance for thiamethoxam.

The use of economic thresholds for applying insecticides is an important Integrated Pest Management practice to limit the probability of the development of resistance and the outbreak of secondary pests. Monzó and Stansly (2017) compared the impact of two economic thresholds for the use of insecticide applications to control ACP: 0.2 and 0.7 psyllids/stem tap samples. Yield increase was observed for samples treated by 0.2 psyllids/stem taps, but there was no significant effect in the case of 0.7 psyllids/stem taps.

Enhanced foliar nutritional programs. Many growers have implemented enhanced foliar nutritional programs in their groves (Gottwald et al., 2012; Stansly et al., 2014). Some studies indicate that foliar nutritional programs can contribute to maintaining the productivity of infected trees by mitigating the nutritional deficiencies caused by HLB (Ozores-Hampton et al., 2017; Rouse et al., 2017). Nutrients such as N, K, Mn, Zn, B, and Mg are widely used for growth and increase the productivity of citrus trees infected with CLAs (Morgan et al., 2016). Applications of macro-nutrients (N, P, and K salts) and micronutrients (primarily B, Mg, and Zn salts) may allow foliage to acquire essential elements that might be limited by root dys-

function. Stansly et al. (2014) reported increased productivity of HLB-affected Valencia orange trees after receiving foliar nutritional sprays.

The use of enhanced foliar nutritional treatments, however, has also been criticized. The cost of foliar nutritional treatments might be greater than the added value of higher yield (Gottwald et al., 2012; Tansey et al., 2017). Morgan et al. (2016) found that yield was most strongly affected by the application of MnSO_4 , but the average yield of the 3-year treatment was slightly higher than that of the unsprayed control. Rouse et al. (2017) evaluated the effects of enhanced foliar nutritional treatments by spraying a mixture of micronutrients, macronutrients, potassium nitrate (KNO_3), and micronutrient package KNO_3 and urea. They found that enhanced foliar nutritional treatments can improve early yield. Stansly and Roka (2013) applied enhanced foliar nutritional treatments to mitigate the debilitating effects of the disease. The isolated effect of foliar nutrition on the yield was negative (-4%), at a total cost of \$643 per acre. The BCR averaged across studies was -0.2, implying it is an inefficient treatment. Using a mixture consisting primarily of micronutrients and macronutrients, Stansly et al. (2014) found that the yield changed from -24% to 23%, with an increased cost of \$729 per acre and an average BCR of 0.4. Ozores-Hampton et al. (2017) demonstrated that the nutritional treatments did not have bactericidal effects on the bacterial pathogen CLAs and only slightly increased the yield by 7% to 9%. Comparatively, the cost of the micronutrient package KNO_3 and urea was \$343 per acre on average. Table 3 shows the reported effects of enhanced foliar nutritional programs on crop yield along with their associated costs. Most studies show that foliar nutritional treatments are not economically cost-effective.

Thermotherapy. Thermotherapy treatment has been proposed to manage CLAs and suppress phytopathogen titers (Yang

et al., 2016). Hoffman et al. (2013) found that the titer of CLAs dropped by more than 40-fold in grapefruit when under 40 °C for 24 h or 42 °C for 19 h for 2 consecutive days. Zhang et al. (2016) reported that exposing HLB-infected Ray Ruby seedlings to 45 °C for 8 h per day for 1 week resulted in significant decreases in phytopathogen titer. Similarly, Fan et al. (2016) showed that if seedlings were exposed to 45 or 48 °C for 4 h on 1 d per week for 3 consecutive weeks, the titer of CLAs within leaves declined by about 30% and 55%, respectively, although it might have caused severe plant tissue damage.

A major challenge with thermotherapy, however, is that it is difficult to perform field treatments. The critical temperature and duration to kill CLAs are still unclear (Ehsani and Pertiwi, 2015; Jia et al., 2017). High temperatures may injure the canopy (Fan et al., 2016); and, more importantly, the root system likely escapes the imposed heat treatment, and the heat will likely not penetrate enough into the thick portion of the bark on the trunk, thus providing inoculum to reinfect the canopy (Chalak et al., 2005). The efficacy of thermotherapy depends on both the above-ground and belowground components of the plant being properly treated (Blaustein et al., 2018). As Yang et al. (2016) demonstrated, combined with antimicrobial compounds, thermotherapy enhanced the delivery efficiency of chemical formulations into the citrus phloem.

Existing studies have discussed the impact of thermotherapy treatments on fruit yield and fruit quality under various temperatures and timings. Al-Jumaili and Ehsani (2015) found that when the surrounding air temperature was increased up to 55 to 65 °C for about 1 to 2 min, the initial results in some samples showed significant changes in juice quality. Longer heating durations resulted in higher brix, but the effects weakened at higher temperatures. Although the acidity of the juice was unaffected by heat treatments, the brix:acid ratio increased significantly at a

Table 3. Impact of foliar nutritional programs on fruit yield and profit.

Treatment	Impact on yield ²	Cost (\$) ³	Benefit (\$) ³	BCR ^w	Location	Reference
N, K, Mn, Zn, B, and Mg	Yield was 45% higher in the 3×/year treatment of N and K, but declined by 25% for the 6×/year treatment of N and K. Yield decreased by 25% from using Mn; there is no significant impact on yield using B and Mg.	—	—	—	FL, 2010–14	Morgan et al. (2016)
Micronutrient to package [potassium nitrate (KNO_3) and urea]	Enhanced foliar nutritional treatments provide some yield benefits, especially in the early years of the trial.	—	—	—	FL, 2010–14	Rouse et al. (2017)
Enhanced nutritional programs (K, Mn, Zn, Cu, and PDS)	ENP might increase disease spread within and between citrus orchards.	\$729.6	\$617.1	0.8	FL, 2009–10	Gottwald et al. (2012)
Enhanced foliar nutrition	Yield was 4% lower than the control group.	\$643.0	-139.8	-0.2	FL, 2009–12	Stansly and Roka (2013)
A mixture consisting primarily of micro- and macro-nutrients	Yield changed from -24% to 23%.	\$729.4	\$7.41	0.4	FL, 2009–12	Stansly et al. (2014)
K-phite, Saver, Mg, Mn, Zn, Mo, K, 435 Oil	Yield increased by 7% to 9%.	\$343.3	\$443.4	1.3	FL, 2011–15	Ozores-Hampton et al. (2017)

²The results are calculated based on data in the existing studies.

³Costs include materials and labor and are adjusted by annual tree density.

³Prices used in calculating benefits are the annual average on-tree price from USDA-NASS.

^wBCR denotes Benefit-to-Cost Ratio.

Table 4. Impact of thermotherapy treatments on fruit yield and profit.

Treatment	Impact on yield ^z	Cost (\$) ^y	Benefit (\$) ^x	BCR ^w	Location	Reference
45 °C for 5 h	Treated trees had a higher yield in midsummer but a lower yield in late summer.		40.5	0.1	FL, 2012	Ehsani et al. (2013)
140 °F for 30 s and 131 °F for 120 s	Heat treatment had an adverse effect on yield in the first year (1% to 6%). Yield reduction was greater in trees treated at a higher temperature.		-1227.8	-2.4	FL, 2015	Ehsani et al. (2016)
55 to 65 °C for 1–2 min	Higher brix; no impact on the acidity; brix/acid ratio increased at a higher temperature or longer duration.		—	—	FL, 2014	Al-Jumaili and Ehsani (2015)
55 °C for 1 h	Mean yield was significantly higher than the yield of HLB-affected trees that were not treated.		—	—	FL, 2015	Ehsani and Pertiwi (2015)
131 °F for 30 s	Fixed cost of the improved thermotherapy system totaled \$54,845; the variable cost per tree was \$2.40 on average, and \$6.50 to \$7.50 for the total.		—	—	FL, 2015	Trotochaud and Ehsani (2016)
131 to 140 °F	Thermotherapy does not improve yield enough to compensate for the damage caused to the canopy.		-410.6	-0.43	FL, 2016–18	Dewdney et al. (2018)

^zThe results are calculated based on data in the existing studies.

^yCosts include materials and labor and are adjusted by annual tree density.

^xPrices used in calculating benefits are the annual average on-tree price from USDA–NASS.

^wBCR denotes Benefit-to-Cost Ratio.

Table 5. Biological control of vector population.

Treatment	Conclusion	Reference
Biological control	Achieving economic efficiency is one of the greatest challenges of biological control.	Bolckmans (2007)
<i>T. radiata</i>	\$0.05 in Brazil	Alvarez et al. (2016)
<i>T. radiata</i>	The total annual costs for operation of the program are estimated at \$361,529 to produce 3.3 million wasps at the cost of about \$0.11 per parasitoid, or \$9.79 per hectare.	Parra et al. (2016)
<i>Bradyrhizobium</i> and <i>Burkholderia</i>	Resident microbiotas affect both the yield and quality.	Trivedi et al. (2010)

higher temperature or a longer duration. Ehsani et al. (2013) developed a prototype of a mobile system that used solar radiation to heat-treat HLB-infected trees in an orange grove. Valencia trees were covered with translucent plastic for a 5-hour heating period that reached 45 °C. The results indicated that treated trees in midsummer had higher yields (30%) than controlled trees. The subsequent study by Ehsani and Pertiwi (2015) found that a treatment of 55 °C for 1 h produced a significantly higher yield than nontreated trees. However, the latest study by Ehsani et al. (2016) suggested that heat treatments had adverse effects on the yield in the first year due to heat-induced fruit drop. Yield reduction was greater (1% to 6%) in trees that were treated at a higher temperature. The results are consistent with a recent study by Dewdney et al. (2018), who concluded that thermotherapy does not improve yield enough to compensate for the damage caused to the canopy. Treatment results of various temperatures and timings are illustrated in Table 4.

The cost of thermotherapy for controlling HLB is reported only by Trotochaud and Ehsani (2016). The estimated fixed cost of the improved thermotherapy system included mobile platform (\$15,000), steam generator

(\$20,000), water storage (\$285), water pump (\$1000), water filter (\$60), water softener (\$2300), electricity generator (\$600), tree enclosure (\$15,000), and electronics (\$600), for a total of \$54,845. The variable cost for operation primarily consisted of labor and fuel, which is \$2.40 per tree on average. The total cost was \$6.50–\$7.50 per tree if renting a machine. Overall, heat treatment had an adverse effect on yield. The estimated benefits from thermotherapy ranged from -\$1788.2 to \$811.8, with a BCR of -1.9 to 0.87 (Table 4).

Biological control. Vector control is considered an essential component of HLB management even in an environment with high disease incidence. Implementing biological control, or combining it with other disease management strategies, such as use of organic amendments, tolerant/resistant cultivars, or pathogen-free certified planting material, may be feasible (Alvarez et al., 2016; Cazorla and Mercado-Blanco, 2016). *Tamarixia radiata* was found to be an effective biocontrol agent against ACP (Chen et al., 2017). *T. radiata* was introduced in Florida, and its control effect on ACP populations is reported to range between 4% and 70% (Gottwald et al., 2007). The convergent lady beetle, *Hippodamia convergens* Guérin-Ménéville, has been released in

Florida, but it is still not commonly used as a biocontrol agent in citrus groves (Qureshi and Stansly, 2011).

A few studies have discussed the cost of parasitoids used for psyllid control (Table 5). Parra et al. (2016) estimated the cost of the biological-control approach in Brazil and found the cost (including all costs involved in the rearing process) was \$0.05 per parasitoid, or \$9.71 per acre. In contrast, the cost in Florida was much higher at \$0.11 per parasitoid (Alvarez et al., 2016). To date, no studies have shown the effect of biological control on yield, so its cost effectiveness is not evaluated in this study.

Other treatments. Despite ongoing efforts made by growers to modify their citrus production practices to control HLB, the phytopathogen has spread to infect most citrus groves (Martinelli et al., 2016; Plotto et al., 2017; Rouse et al., 2017). Other proposed treatments for coping with HLB include tree removal and pruning, interplanting crops, and transgenic biotechnology.

According to some scientists, tree removal and pruning are the most effective treatment for controlling ACP populations (Gottwald, 2010), but this approach is not cost efficient and is difficult to implement in practice because it needs coordinated efforts from neighboring growers (Table 6). For example, Muraro (2010) estimated the increased grove maintenance costs for eradicating infected trees at about \$450 per acre. Roka et al. (2010) reported that the per-acre cost increase in grove maintenance associated with tree replacement ranges from \$200 to \$600 per acre. Moreover, the study by Ozores-Hampton et al. (2017) found that although yields from pruned trees were higher than yields from nonpruned trees, the total cost of pruning was estimated to be \$160 per acre.

Other scientists have suggested that infestations of psyllids in citrus can be reduced

when citrus is interplanted with guava (Ahmed et al., 2013; Tsai et al., 2013), which apparently inhibits the psyllid vector (Beattie et al., 2006). Gottwald et al. (2014) found a significant reduction in Asian citrus psyllid infestation in citrus interplanted with pink guava, but there was no reduction in Asian citrus psyllid infestation when citrus was interplanted with white guava. However, interplanted citrus with either white or pink guava did not prevent the introduction and spread of HLB.

A potential long-term solution to HLB is the development of transgenic citrus. One such proposal intends to develop a citrus variety that overexpresses the *Arabidopsis thaliana* NPR1 gene to regulate systemic acquired resistance (Dutt et al., 2015). Overexpression of modified plant thionins with antimicrobial activity has also been reported to enhance HLB resistance (Hao et al., 2016).

While gene-editing tools, such as the CRISPR-Cas9, are being researched to create citrus cultivars that are less susceptible to CLAs or to express genes that may prevent vector transmission, transgenic biotechnology is costly (Wang et al., 2017; Zhang et al., 2017). It is also important to consider that the adoption of biotechnology on citrus will very likely present challenges in the marketplace because some consumers are strongly averse to it.

Economic Performance of Treatments

Figure 2 illustrates the range for costs, benefits, profits, and BCRs associated with each type of treatment based on data available in the studies reviewed (Tables 1–4). The number of observations analyzed for antibiotics, insecticides, foliar nutritional programs, and thermotherapy are 74, 38, 26, and 80, respectively.

The cost of insecticide sprays ranges between \$100 and \$500 per acre, making it the cheapest treatment among the four major treatments analyzed. The costs of using antibiotics and nutritional supplements reported in the literature were similar and fluctuate between \$350 and \$660 per acre. With a cost of \$850–\$1000 per acre, thermotherapy represents the most expensive treatment proposed for coping with HLB.

The studies reviewed in this article report a positive impact on yield for most treatments, which translates into a potential revenue increase. In particular, the estimated medians of benefit (i.e., revenue) generated by applying antibiotics, insecticides, and foliar nutritional supplements range between \$200 and \$300 per acre. Even though the estimated revenue of using antibiotics is slightly higher than that of insecticide sprays and foliar nutritional supplements, the differences are not significant. Thermotherapy is the only treatment that has been found to have an adverse effect on yield. The fact that the critical temperature and duration needed to kill the bacteria in trees are still unclear (Ehsani and Pertiwi, 2015) further jeopardizes the feasibility of the treatment.

To evaluate whether a treatment is economically feasible in the field, it is necessary to calculate its estimated profit (revenue minus cost). The median profits obtained from the use of antibiotics, insecticides, and foliar

Table 6. Other treatments for controlling HLB.

Treatment	Conclusion	Reference
Tree removal and pruning	Grove maintenance costs are about \$450 per acre. Replacement cost is \$200–\$600 per acre. Tree removal is \$566–\$680 per acre.	Muraro (2010) Roka et al. (2010) Monzó and Stansly (2017)
Interplanting	\$1–\$3 per tree in Brazil Yield in interplanted orchards is higher than in noninterplanted orchards.	Belasque et al. (2010) Gottwald (2010)
Transgenic biotechnology	Induces effects on target insects but is costly	Hajeri et al. (2014)

Fig. 2. Comparison of benefits and costs of the proposed treatments against HLB. The results are estimated based on data available in the studies reviewed. Superscript dots are the outliers of the results in each treatment. The number of observations for antibiotics, insecticides, foliar nutritional programs, and thermotherapy are 74, 38, 26, and 80, respectively.

Table 7. *t* test for the measurements between treatments.^z

		Antibiotic	Insecticide	Foliar nutritionals
Cost	Antibiotic	—	—	—
	Insecticide	2.86**	—	—
	Foliar nutritionals	1.36	1.21	—
	Thermotherapy	11.75***	9.71***	10.50***
Benefit	Antibiotic	—	—	—
	Insecticide	7.40	—	—
	Foliar nutritionals	3.68**	6.62***	—
	Thermotherapy	6.29***	8.23***	15.46***
Profit	Antibiotic	—	—	—
	Insecticide	0.11	—	—
	Foliar nutritionals	1.58	0.68	—
	Thermotherapy	10.60***	0.68***	5.97***
BCR	Antibiotic	—	—	—
	Insecticide	1.05	—	—
	Foliar nutritionals	1.39	1.28	—
	Thermotherapy	10.90***	5.73***	7.28***

^zThe reported values are the *t*-static between two treatments; Ho: mean(diff) = 0; ***P* < 0.05, ****P* < 0.01.

nutritionals are estimated at −\$251, \$28, and −\$411 per acre, respectively. Because there was no positive yield effect when using thermotherapy, the treatment is not economically feasible. The median values of the BCR for antibiotics, insecticides, foliar nutritionals, and thermotherapy are 0.60, 1.12, 0.63, and −1.99, respectively. BCR values smaller than one imply that the cost outweighs the benefit.

In Table 7 we report the results of a test on whether the means are statistically different for the treatments in each of the measurements in Fig. 2. The results show that for any two comparisons of antibiotics, insecticides, or foliar nutritional programs, the means for profits or BCR are not statistically different. However, the means for cost, benefit, profit, and BCR for thermotherapy were statistically different from any of the other three treatments. The application of antibiotics and insecticides resulted in significant differences in terms of costs and benefits, but profits and BCR were not statistically different. Antibiotics and foliar nutritionals, as well as foliar nutritionals and insecticides, were only statistically different in terms of benefits.

Biological control is an inexpensive strategy, but there are no data on how it affects yield (Al-Jumaili and Ehsani, 2015; Lin et al., 2010). Also, while it has been found that the spread of disease might be contained by removing infected trees (Warnert, 2012), the cost of such practice is relatively high, and the economic losses derived from yield reduction due to tree removal are even larger. However, high-density plantings have been found to be a profitable strategy to mitigate the impact of HLB (Singerman et al., 2018). A treatment that has been recently incorporated by citrus growers in Florida (and for which there is still no data) is referred to as “nutritional spoon-feeding”; this basically involves providing trees with high frequency but low doses of fertilizer. Some scientists are testing growing citrus trees under enclosed structures to prevent HLB infection (Ferrarezi et al., 2019; Schumann et al., 2019). While such a strategy has a high establishment cost, preliminary results show it is profitable for growing fresh fruit

(Schumann et al., 2019). Growers and researchers are testing individual protective covers to protect young citrus trees from becoming infected with HLB. Finally, disease-resistant or tolerant varieties have also been proposed as a long-term solution to the disease; but without data on this solution’s impact on yield, its cost-effectiveness cannot be investigated.

Conclusions and Discussion

The outbreak of HLB has significantly impacted the citrus industry, particularly in Florida but also in Brazil (the world’s largest orange producer). Recently, the disease has started to spread throughout California. While there is still no cure for HLB, scientists have proposed different treatments to manage the disease. Thus, in this study we reviewed some of the major treatments that have been proposed, and we found that their profitability varies widely. We found that broad-spectrum insecticides provide the only cost-effective strategy for mitigating the impact of the disease. Citrus-growing regions in which the spread of the disease is incipient can use the lessons learned in Florida to be more effective in coping with HLB and to avoid a similar outcome. In addition, the combination of treatments such as nutrients and antibiotics (Zhang et al., 2019), insecticide and foliar nutrients (Tansey et al., 2017), and biological control with chemicals (Kumar et al., 2017) have been conducted in recent studies and were found to have complementary effects and a better performance on control of the ACP and yield increment. Whether those combinations of treatments are cost-effective could be addressed in future studies.

While individual applications of synthetic pesticides have allowed growers to manage many pests effectively and cheaply (Smith et al., 1976), there are, however, some caveats to be noted with respect to their intensive use. Using site-specific sprays is not optimal when managing invasive species because the effectiveness of individual uncoordinated pest control is compromised by the mobility of pests (Vreysen et al., 2007).

Therefore, growers’ ability to control the ACP and HLB depends on the actions of neighboring growers (Singerman et al., 2017). Government top-down regulation or a collective action can help growers coordinate their efforts and be more effective (Singerman and Rogers, 2020). Another important aspect to consider is that the intensive use of pesticides has an additional cost to that included in their market price; those costs include potential ecological harm, excessive chemical residue in the fruit, and the development of resistance. Therefore, cooperation among neighboring growers for the control of the ACP—for example, through an area-wide spraying program—can not only be more effective, but also contribute to lessening those additional costs, making society as a whole better off.

It is worth noting that besides the threat posed by HLB, there are also other challenges that affect the entire specialty crop industry, including intensifying foreign competition (Suh et al., 2017; Wu et al., 2018a, 2018b) and labor shortages (Cao et al., 2019; Wu et al., 2015), which add further concerns to the industry’s economic outlook. For example, recent data from the USDA-ERS show that Mexico’s exports of orange juice to the United States have increased dramatically in the last few years, and this trend is expected to continue. Coordinated actions and policies are needed to address these threats to the industry to ensure its long-term sustainability.

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