Agric Res (June 2016) 5(2):109–118
DOI 10.1007/s40003-016-0204-z

REVIEW

Citrus Greening Disease (Huanglongbing) in Florida: Economic Impact, Management and the Potential for Biological Control

Sergio Alvarez[1] · Eric Rohrig[2] · Daniel Solís[3] · Michael H. Thomas[3]

Received: 22 October 2015 / Accepted: 21 January 2016 / Published online: 12 March 2016

Abstract This review focuses on the impact of citrus greening disease in the state of Florida and provides information to develop an economic analysis of pest management options for the control of this disease. In doing so, we review the history, evolution and severity of citrus greening in Florida with particular emphasis on the management alternatives to combat this disease, including increased use of pesticides and classical biological control. We also discuss the institutional framework that has been set up by the state and federal agencies and the citrus industry to slow the spread of citrus greening. While the use of classical biological control for citrus psyllid has not been as successful as some other biological control programs, its implementation fits well in a mixed strategy management plan to control this disease.

Keywords Citrus · Biological control · Huanglongbing · Disease management

Introduction

Citrus greening disease or Huanglongbing (HLB) is a destructive vector-borne disease that affects all varieties of citrus and is currently threatening the existence of Florida (FL)'s citrus industry. While HLB was not discovered in FL until August 2005 [3], its vector has been present in the state since at least 1998 and has widely spread throughout the citrus producing regions of the state by 2003 [10]. The disease has spread rapidly and is now present in every citrus producing county in FL. In addition, HLB has also been found recently in or near urban areas in Brownsville and Houston, Texas, as well as Los Angeles, California. Outside FL, HLB is presently contained and has not yet affected other major citrus producing states. Other geographical areas suffering from HLB include citrus producing regions of Africa, Brazil, the Middle East, the Indian subcontinent and Southeast Asia [3].

There is no known cure for HLB, and the three major components of traditional HLB management include control of the insect vector through chemical or other means, aggressive removal of infected trees to reduce sources of inoculum within groves, and planting of disease-free nursery stock [9]. However, replanting trees and getting them into production without contracting HLB is costly and difficult even under intensive insecticide programs, making producers reluctant to follow the traditional three-tier system and instead choosing not to remove diseased trees if they remain productive. Some growers have implemented an alternative strategy to supply diseased trees with macro- and micronutrients through foliar sprays to suppress disease symptoms [14].

The views and opinions expressed or implied in this article are those of the authors and do not necessarily reflect the position of the Florida Department of Agriculture and Consumer Services nor the USDA Animal Plant and Health Inspection Service.

✉ Sergio Alvarez
Sergio.Alvarez@freshfromflorida.com

1 Office of Policy and Budget, Florida Department of Agriculture and Consumer Services, 407 S. Calhoun Street, Tallahassee, FL, USA

2 Division of Plant Industry, Florida Department of Agriculture and Consumer Services, Gainesville, FL, USA

3 Agribusiness Program, College of Agriculture and Food Sciences, Florida A&M University, Tallahassee, FL, USA

In this paper, we examine the costs and benefits of vector control through biological means. While the favored method for controlling the insect vector of HLB is through insecticide use, there are a number of organisms that are known to be effective predators or parasites of the vector. One of these organisms, the parasitoid wasp *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophiadae), was chosen by the FL Department of Agriculture and Consumer Services (FDACS) Division of Plant Industry (DPI) to be reared for mass release among citrus producers in the state [23, 33].

We review the biology and epidemiology of HLB and its impact on the citrus industry in FL, current HLB management strategies in FL, as well as the institutional framework that has emerged for treatment and control of citrus diseases in the state, including HLB. We also discuss the classical and augmentative biological control programs that have been used in FL to combat citrus greening disease, along with the costs and benefits of these strategies.

The HLB Disease and Its Impact in Florida

HLB is caused by phloem-restricted bacteria of the *Candidatus* Liberibacter group, of which at least three different species are known to occur: an Asian strain (*Candidatus* Liberibacter asiaticus), an African strain (*Candidatus* Liberibacter africanus) and a strain found only in Brazil (*Candidatus* Liberibacter americanus). These three species of bacteria can be transmitted by two species of citrus psyllids: Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) and African citrus psyllid, *Trioza erytrae* (Del Guercio) (Hemiptera: Triozidae), although the bacterial and vector species are geographically isolated and only overlap in a few locations such as the islands of Mauritius and Reunion in the Indian Ocean [3].

In FL's HLB outbreak, *D. citri* is the only vector present and *Ca*. L. asiaticus is the bacterial species identified as the causal agent [3, 15]. Trees infected with HLB first exhibit yellow shoots and blotchy mottle leaves reminiscent of nutrient deficiencies, and fruits on affected branches are small and lopsided, produce aborted seeds, do not change color properly and drop prematurely [3]. As the disease progresses, the tree loses productivity as entire branches, and then the whole tree, die. If the disease is widespread, citrus trees may live for only 5–8 years and never produce usable fruit [36].

The Asian citrus psyllid depends heavily on new flush from citrus species for survival and reproduction. *D. citri* females deposit their eggs only on young tissue and can lay up to 800 eggs during their lifetime. Eggs hatch in 4 days or less, and the larval stage consists of five instars that are completed in 15 days or less, after which mature adults emerge. The length of the life cycle is dependent on temperature, but normally lasts between 15 and 47 days [21].

While *D. citri* is generally considered poor fliers and can only fly over distances of one mile in several days [2], their long range dispersal is aided by prevailing winds and unintended human transport of host plant material. For instance, it is believed that natural dispersal alone—aided by prevailing winds—is responsible for the spread of HLB-carrying psyllids from urban coastal southeast FL to commercial citrus groves in Hendry county, which is located more than 50 km away on the opposite end of the FL Everglades, an area with no known psyllid hosts [11, 13]. It is also believed that *D. citri* was able to establish widely in FL as a result of shipments of the ornamental bush orange jasmine (*Murraya paniculata*) infested with Asian citrus psyllid nymphs and adults that were grown in southern Miami-Dade County and were later sold in discount chain stores throughout the state [12].

Even though HLB is vector transmitted, there are a number of features of this disease that make control especially difficult. For instance, once a healthy tree is infected, there is a latency period that can last between 6 and 12 months in which the tree exhibits no symptoms but may act as a source of the pathogen [3]. This reduces the effectiveness of management strategies in which symptomatic trees are removed to eliminate sources of inoculum within a grove [9].

The feeding and reproductive behavior of *D. citri* also plays an important role in the spread of the pathogen. *D. citri* adults prefer emerging plant tissue—known as flush—for food, and oviposition and immature psyllid development occurs only on soft flush [10]. This preference for fresh flush makes young trees particularly susceptible to infestation by psyllids and hence to inoculation with the HLB pathogen. Trees infected with HLB produce yellow shoots and release a volatile methyl salicylate compound, both of which attract *D. citri* adults [22]. However, since HLB-infected tissue has a relatively poor nutritional content, adult psyllids quickly move on to flush of healthy nearby trees, a behavior which fosters the spread of the disease [22]. Psyllids carrying the HLB bacterium have also been found to develop faster and lay more eggs, resulting in more rapid population growth [31].

The transmission of the HLB bacterium from infected trees to psyllids and from psyllids to healthy trees also follows some interesting dynamics. For example, the transmission efficiency of HLB from carrier adult *D. citri* to healthy trees is highly variable, ranging between 1 and 80 % [44]. There is also a latency period between the moment in which an adult psyllid acquires the pathogen and the time in which the psyllid can transmit to a healthy tree [17, 18]. In addition, there is also a difference in transmission efficiency between psyllids that acquire the

HLB pathogen as adults and those that acquire the bacteria during the larval stages, with the latter having significantly higher transmission efficiencies [18, 32]. Furthermore, psyllids that acquire the HLB bacterium during the larval stage can transmit the pathogen as soon as they emerge as adults [44].

While the true impact of HLB on citrus production in FL is difficult to determine, it is clear that disease has had a significant impact in the decline of citrus acreage in the state (Fig. 1). Total area planted in citrus peaked in 1995 at 330 thousand hectares (815 thousand acres) and declined slowly until 2001, when 290 thousand hectares (718 thousand acres) were planted throughout the state. There has been a marked acceleration in the decline of citrus acreage since that time, and by the 2012–2013 season, less than 198 thousand hectares (490 thousand acres) of citrus remained in production. Statewide citrus production has suffered a similar decline, going from 304 million boxes in the 1997–1998 season to 156 million boxes in the 2012–2013 season. All told, citrus acreage has decreased by 40 % and production by 49 % since their historical peaks, all of which occurred in the last 20 years.

There are a number of factors that have contributed to this observed decline in production area and productivity of citrus in FL. In addition to HLB, citrus canker, another adventive bacterial disease, has been affecting commercial citrus groves in FL since at least 1995 [4]. Recent changes in consumer preferences toward beverages with high sugar content may also be playing a part in the decline of FL's citrus production, of which a vast majority is destined for processed juice products.

Monetary estimates of the impact of HLB on FL citrus have begun to emerge in recent years. Hodges and Spreen [16] used a programming model of the global citrus market to estimate the price and quantity of orange juice that would have been observed in the absence of HLB and compare it with the actual price and quantity between the 2006–2007 and the 2010–2011 harvest seasons, and estimated a production loss of $1.7 billion over this 5-year period. Similarly, Moss et al. [24] developed estimates of lost producer and consumer surplus as a result of the current outbreak of HLB, and concluded that in the 2012–2013 season, consumers and producers lost an estimated $1 billion. Some of the economic challenges of HLB in FL are further summarized in Farnsworth et al. [5].

HLB Management in Florida

Current strategies for citrus disease management in FL have been shaped by previous efforts to control and eradicate diseases of citrus in the state, in particular the effort to eradicate citrus canker bacterium, *Xanthomonas axonopodis* pv. *citri*. This pathogen was detected in residential areas surrounding Miami International Airport in 1995, and a joint Federal and State government eradication program was rapidly developed and implemented. This program called for the removal of all diseased citrus trees, in addition to all citrus trees within 580 m (1900 feet) of diseased trees. The United States Department of Agriculture (USDA) administered the eradication program for commercial groves and provided compensation of $26 per removed tree to affected producers. Similarly, FDACS was tasked with administering the eradication program for residential orchards and provided compensation of $55 per removed tree. However, legal challenges from homeowners were filed very early in the eradication program, and by the year 2000, the courts halted the eradication program in residential areas [1]. Eradication was finally declared infeasible in 2006 after severe hurricane seasons in 2004 and 2005 had aided the spread of the pathogen throughout all citrus producing areas in the state, and legal action by homeowners seeking further compensation for loss of trees

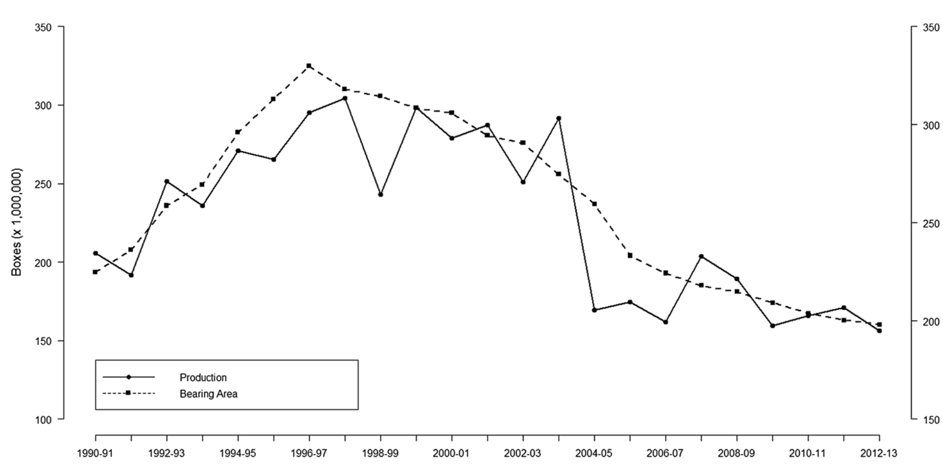

Fig. 1 Citrus production and bearing hectarage in Florida, 1990–1991—2012–2013. *Source:* USDA-NASS [6]

continues to this day. The problematic precedent set by the citrus canker controversy in FL from a disease management perspective is that the state has very limited powers when it comes to eradicating citrus diseases if tree removal is required.

Traditional management of HLB includes control of the psyllid vector, aggressive removal of infected trees to reduce sources of the disease, and planting with HLB-free nursery stock. This management scheme has proven successful in Brazil and has resulted in drastic reductions in the proportion of symptomatic trees [3]. While this three-pronged approach was advocated early on in FL's HLB outbreak, it was deemed to be too expensive by most producers, who instead decided to maintain symptomatic trees as long as they were bearing usable fruit [14]. Given the precedent set by the citrus canker eradication program, the state is unable to force the removal of diseased trees to curtail the spread of the pathogen.

There are some institutional aspects of citrus disease management in FL that are worth mentioning. First, citrus disease management in the state is governed by the Citrus Health Response Plan (CHRP), a policy developed jointly by FDACS and USDA in consultation with the citrus industry. Recognizing that FL's citrus industry is at particular risk of potentially damaging biological invasions and that eradication of these pathogens and pests is not always feasible, these organizations developed the CHRP as a plan that emphasizes prevention and management of disease through registration, inspection and certification of entities involved in the production and commercialization of citrus, from nurseries and budwood facilities to processors and distributors of fresh citrus and other citrus products [42]. All if not most citrus disease management strategies in the state are funded and implemented under the auspices of the CHRP.

Second, the state of FL established a series of Citrus Health Management Areas (CHMA) in response to recommendations by a National Research Council panel tasked with developing strategies to help the state cope with HLB [29]. The primary objective of the CHMAs is to provide regional coordination for insecticide sprays to control populations of the Asian citrus psyllid by removing sources of refuge and re-infestation [19]. Both of these policies ensure that Federal and state agencies are constantly inspecting and monitoring populations of Asian citrus psyllids throughout the state and that this monitoring takes place in a decentralized manner by focusing on particular CHMAs.

Conventional citrus groves in the state have adopted a regime of heavy pesticide use for controlling *D. citri* populations that involves 8–12 foliar applications annually [5]. The most effective chemicals for control of Asian citrus psyllids have proven to be the broad-spectrum pesticides such as pyrethroids, organophosphates and neonicotinoids [9]. In recent years, regionally coordinated insecticide spraying throughout the CHMAs during the winter, when low temperatures slow down the life cycle of psyllids to near dormancy, has been especially effective at reducing *D. citri* densities in commercial groves [19].

In addition to heavy insecticide use throughout the year to control the psyllid vector of HLB, many conventional groves are also implementing a nutritional supplement regime that is applied through foliar sprays [37]. This type of foliar supplementing of macro- and micronutrients has yielded positive effects with other annual crops suffering fungal and bacterial diseases, but any benefits it may have on HLB-infected citrus are only anecdotal, and controlled trials have thus far failed to show significant benefits [8]. This strategy has the added problem of ensuring a buildup of HLB inoculum in the grove, thereby threatening the success of reset plantings [39] as well as increasing overall production costs.

Another component of HLB management in FL is the control of *D. citri* populations through the introduction of natural enemies from its native range. In particular, two parasitoid wasps from Asia and the Indian subcontinent were introduced to FL in 1999, shortly after the discovery of the Asian citrus psyllid. These wasps, *Tamarixia radiata* and *Diaphorencytrus aligarhensis*, lay their eggs on the underside and inside, respectively, of *D. citri* larval nymphs. Upon egg hatch, the wasp larva parasitizes and eventually kills the *D. citri* nymph while completing its development to the adult stage. While both wasps were introduced at the same time, only *T. radiata* has successfully established in FL, and today can be found in commercial citrus groves throughout the state [33]. It is important to note that both of these wasps are host-specific parasitoids of *D. citri* and they require the presence of Asian citrus psyllid nymphs for oviposition and completion of their life cycle. In the absence of *D. citri* nymphs, both of these wasps would be incapable of reproducing and hence would be subject to local extinction.

Biological Control of HLB in Florida

Biological control is the study, importation, augmentation and conservation of natural enemies to regulate the population densities of pests or disease pathogens [30]. Importation biological control, also known as classical biological control, involves the identification of a natural enemy from an invasive pest's native range and the subsequent importation and release of the natural enemy in the introduced range. Conservation biological control involves the modification of production practices to enhance survival of natural enemies, and includes modification of pesticide regimes and manipulation of habitat through special plantings and tilling practices. Augmentative biological control involves the mass rearing of natural enemies to 'augment' their populations at crucial periods to suppress pests.

Biological control efforts against the Asian citrus psyllid in FL began simply as a classical approach with the importation and release of *T. radiata* in July of 1999 and *D. aligarhensis* in March of 2000. Of these two parasitoid wasps, only *T. radiata* became widely established [33], possibly due to competition between the two parasitoids [35]. In recent years, FDACS has improved the methodology of mass rearing *T. radiata* to the point where an augmentative release biological control program has become feasible. In addition to *T. radiata*, a number of insects native to FL are known predators of *D. citri*, including several species of ladybeetles and spiders [23].

FDACS operates two facilities dedicated to the mass rearing of *T. radiata* wasps for release throughout FL's commercial citrus groves and residential areas. The smaller facility, located in Gainesville, on the northern edge of FL's citrus growing region, produces an estimated 125,000 *T. radiata* adults each month, with no space for additional expansion. A new facility located in the central FL community of Dundee in the heart of the state's citrus producing region currently produces an estimated 150,000 *T. radiata* adults monthly, but is set to expand and increase its rearing capacity by a factor of three.

Adult parasitoid wasps are offered free of charge to producers and homeowners interested in using augmentative releases of *T. radiata* to control populations of Asian citrus psyllid in their property or nearby areas. While a majority of commercial citrus groves are under heavy insecticide regimes that preclude the establishment and survival of *T. radiata*, commercial producers, dooryard citrus owners and orange jasmine hedge owners following organic practices and low or no insecticide spray regimes can benefit from augmentative releases of *T. radiata* as a means to control psyllid populations. Parasitoid releases in areas not under effective psyllid management indirectly benefit nearby commercial growers by reducing psyllid populations which may disperse into their production areas, thereby increasing pest pressure in their grove. There is also a temporary need for non-toxic psyllid control during the spring flush season when citrus trees are also blooming, as heavy insecticide sprays will result in pollinator mortality, low pollination rates and hence low fruit yields [20].

There is also an important component of the CHRP program that relies on *T. radiata* wasps reared in FDACS facilities. Through the surveys conducted under CHRP, state officials and extension scientists can identify certain locations as 'hotspots' where psyllid counts are abnormally high, indicating large population densities of the HLB vector [19]. These surveys also allow the identification of still flushing abandoned groves or feral citrus located in private property, and where the landowner cannot be reached or is not willing to cover the expense of insecticide sprays [20]. In these cases, augmentative releases of *T. radiata* by CHRP field inspectors and other interested individuals can reduce psyllid populations.

The operational costs of FL's *T. radiata* mass rearing program have been documented by Kerr et al. [20], who separate these costs by different categories and by facility (Table 1). Each of these facilities employs one biological scientist and three laboratory technicians, which comprise over 75 % of the operational costs of the program. The remaining portion of the operational costs are dominated by utilities, shipping—which includes shipping supplies and charges for overnight shipping of live wasps to requesting parties and pre-paid return service postage for the shipping materials—and other supplies that include soil, pots, pesticide, fertilizer and light bulbs. The total annual costs for the operation of the program are estimated to be $361,529 to produce 3.3 million wasps at a cost of approximately $0.11 per parasitoid.

Evaluating the impact that the mass rearing and augmentative release of *T. radiata* has had on FL's HLB epidemic is a complex task that is yet to be undertaken. Many variables must be examined such as location of commercial citrus relative to other psyllid host sources, psyllid management practices, local weather patterns, current incidence of disease in or nearby the grove, psyllid population numbers in or near the grove and general tree health as it relates to flush production. Measuring the effectiveness of augmentative releases of *T. radiata* on the spread of HLB would require a Herculean effort of testing every tree in a designated research plot for the disease before, during and following the experiment and performing insect counts for a long time period, all while excluding *T. radiata* from control groves and preventing movement of both insects between experimental plots and the outside world. Currently, HLB incidence is extremely high in FL with growers reporting over 90 % of acres and over 80 % of trees being HLB positive [38], making it difficult to track its spread at any single location since most trees are infected. Resources and funding thus far have not been forthcoming for a study of that magnitude. Up to date, the most comprehensive study of the impact of *T. radiata* is Michaud's [23] field survey of natural mortality of *D. citri* in central FL.

To determine the relative contribution of *T. radiata* to juvenile psyllid mortality, Michaud [23] surveyed citrus trees in several central FL commercial groves to determine the infestation by *D. citri* nymphs and surveyed infested trees continuously to determine natural mortality rates of juvenile psyllids, as well as the relative contribution of

Table 1 Annual costs of Florida's *Tamarixia radiata* mass rearing program

Item	Cost
Dundee facility	
Labor	$147,000.00
Electricity	$19,000.00
Phone	$724.29
Propane	$2009.13
Other utilities	$1795.80
Shipping	$6000.00
Supplies	$15,000.00
Subtotal	$191,529.22
Item	Cost
Gainesville facility	
Labor	$129,000.00
Electricity	$20,000.00
Shipping	$6000.00
Supplies	$15,000.00
Subtotal	$170,000.00
Total	$361,529.22

Source: Kerr et al. (2014)

different natural enemies to psyllid nymph mortality. To determine the contribution of *T. radiata* parasitism in particular, Michaud utilized a set of field cages that would allow *T. radiata* adults to move in and out, but would prevent all other natural enemies from reaching the nymphs contained in the cage.

The results from this field experiment are remarkable in that they show two surprising findings. First, *T. radiata* is but a minor contributor to natural mortality of psyllid juveniles in FL, and only about 1 % of natural psyllid mortality can be attributed to *T. radiata* parasitism. Second, FL has a large number of native organisms that are taking advantage of the presence of the Asian citrus psyllid and using them as a source of food. These organisms, which include ladybeetles, spiders, and ants, are altogether responsible for natural mortality rates in juvenile *D. citri* as high as 90 % [23]. It is important to note, however, that there were no augmentative releases in any of Michaud's [23] study areas, the study was conducted before HLB was discovered, and growers began relying heavily on frequent insecticide sprays which wipe out all natural enemies, and at the time, the *T. radiata* biological control program in FL was limited to a classical approach utilizing small, infrequent releases. Therefore, the results of a similar study in a commercial grove following augmentative releases may yield different results. Similarly, Michaud's [23] study measured the impact of natural enemies on *D. citri* mortality, but their impact on the spread of HLB was not assessed since HLB had not been detected in FL at the time.

Even in the face of Michaud's [23] findings, the new reality of increasing ACP resistance to pesticides is in itself a good reason to continue developing a biological control program for Asian citrus psyllid in FL. For instance, Tiwari et al. [40] found lower susceptibility to commonly used insecticides such as bifenthrin, carbaryl, chlorpyriphos, fenpropathrin, imidacloprid, spinetoram and thiamethoxam in Asian citrus psyllid populations from commercial groves collected in 2009 and 2010 than in a control laboratory-reared population established with insects collected in 2000. The fact that psyllid populations exposed to insecticides developed resistance to these chemicals in 10 years or less highlights the importance of an integrated pest management approach for the future control of HLB in FL.

Natural enemies of the Asian citrus psyllid, including *T. radiata*, also play an important role in controlling both the vector and the spread of the HLB pathogen in urban and suburban environments, where homeowners are unlikely to use insecticides and *D. citri* populations would grow unchecked in the absence of its natural enemies. In fact, citrus trees in urban and suburban areas are known to be important latent sources of disease, and high foreclosure rates, which are associated with poorly or unmanaged landscaping, are known to facilitate the spread of Asian citrus psyllids [34]. Additionally, orange jasmine hedges, common in central and south FL, are often irrigated and trimmed frequently inducing the growth of new flush available for psyllid reproduction year round. Therefore, releases of *T. radiata* in commercial orchards may be providing a positive externality to dooryard citrus owners by helping to establish populations of the parasitic wasps that can migrate to urban and suburban areas. But more important, releases of *T. radiata* in urban and suburban areas may provide commercial citrus growers a sizable positive externality by reducing latent psyllid populations and mitigating the spread of HLB.

While it is still unclear whether the benefits of the *T. radiata* mass rearing and augmentative release program exceed its costs, we can definitively state that the parasitic wasp *T. radiata* is not the silver bullet that biological control enthusiasts and FL's citrus producers were hoping for. It is very likely that *T. radiata* is exerting significant pressure on Asian citrus psyllid populations throughout the state, especially through the augmentative release of parasitic wasps at critical periods of citrus flushing and psyllid oviposition. Similarly, the augmentative release of *T. radiata* wasps may be the only reasonable way to control psyllid populations during citrus blooming periods when use of insecticides would cause severe mortality in pollinating insects—particularly honeybees—and therefore

Table 2 Insecticide spray programs used in Florida oranges for the 2011–2012 season

Date	Product applied	Active compound	Chemical family	Spray method	Spray costs per hectare	
					Southwest	Central
First flush or February	Danitol	Fenpropathrin	Pyrethroid	Fixed wing aerial	$61.83	$84.98
Late March or early April–post bloom	Dimethoate	Dimethoate	Organophosphate	Air blast	$139.69	$160.96
Late April or early May	Mustang	Zeta-cypermethrin	Pyrethroid	Air blast	$107.81	$125.90
April or May	Dimethoate	Dimethoate	Organophosphate	Ground low volume	$31.11	$32.44
Mid to late May	Dimethoate	Dimethoate	Organophosphate	Air blast	$99.86	$128.20
Early to mid June–first summer oil	Mustang, Movento	Zeta-cypermethrin, Spirotetramat	Pyrethroid	Air blast	$233.09	$263.71
Late July or August–second summer oil	Provado	Imidacloprid	Neonicotinoid	Air blast	$149.94	$172.26
September	Delegate	Spinetoram	Spinosyn	Air blast	$138.97	$160.20
Late September or October	Malathion	Malathion	Organophosphate	Fixed wing aerial	$142.33	
Late October or November	Imidan	Phosmet	Organophosphate	Fixed wing aerial	$45.27	$66.74
February or november	Danitol	Fenpropathrin	Pyrethroid	Fixed wing aerial	$61.83	$71.31
February or November	Malathion	Malathion	Organophosphate	Fixed wing aerial	$33.04	$35.04
February or November	Malathion	Malathion	Organophosphate	Ground low volume		$53.30
Total					$1244.77	$1355.05

Source: Muraro [25–28]

result in lower fruit yields and economic losses to FL's significant orange blossom honey industry.

The relative costs and benefits of the *T. radiata* mass release program may be better viewed in comparison with the available alternatives for psyllid control. As discussed previously, most conventional citrus growers are currently relying on multiple insecticide sprays every year to maintain *D. citri* populations as low as possible. Before the introduction of HLB, conventional citrus growers would spray insecticides between two and three times a year. However, in recent years the insecticide spray frequency for these same growers has increased drastically, and more than 12 annual sprays are now common in FL orange groves.

A telling illustration of this increase in sprays and its associated costs can be made using the annual citrus budgets prepared by Muraro [25–28]. During the 2003–2004 production season, the citrus budgets for Southwest and Central FL, the main orange producing regions in FL, included between one and three sprays, depending on whether the product was destined for the fresh or processed market, with the heavier spray regimes favoring product for the fresh market. The total costs for these sprays ranged between $215.23 per hectare for the single spray regime to $523.67 per hectare for the three spray regime, and none of these sprays contained any organophosphates or neonicotinoids, two of the main types of insecticides in use today, but instead contained copper-based insecticides. On the other hand, the 2011–2012 citrus budgets for these same regions included 12 insecticide sprays containing pyrethroids, organophosphates, neonicotinoids and spinosyns with total costs ranging between $1244.77 and $1355.05 per hectare (Table 2). Given the continued spread of HLB and consequent decline of citrus throughout the state of FL over the past 10 years, it would be equally difficult to weigh the costs and benefits of the increased use of pesticides as it is to weigh the costs and benefits of the *T. radiata* mass rearing program.

Discussion

Our review of FL's *T. radiata* mass rearing program illustrates the difficulty in measuring the net benefits of biological control programs targeting insect vectors of disease or that do not result in complete suppression of the target pest. An additional difficulty in measuring the net benefits of the program stems from the complexity of the HLB disease system, where inducing a high percentage of juvenile mortality of the target pest—the vector of the HLB pathogen—does not result in meaningful reductions in the incidence of the disease.

Field experiments have shown that classical biological control of *D. citri* using *T. radiata* as an introduced control agent results in suppression of the target pest—albeit causing relatively low mortality rates. However, given that *T. radiata* requires Asian citrus psyllid nymphs for completion of its life cycle, its mere persistence in FL's citrus groves is an indication that the parasitoid wasps are an effective natural enemy of *D. citri*. Therefore, it is clear that natural enemies, native generalist predators and introduced parasitoid wasps, account for significant suppression of Asian citrus psyllid populations.

The effectiveness of augmentative releases of *T. radiata* in mitigating the impacts of HLB is perhaps best assessed in comparison with the other available options for managing and controlling the disease. Federal and state agencies, universities and FL citrus growers have spent a considerable amount of resources in the fight against HLB. A large number of strategies have been implemented, including heavy insecticide use, quarantines and nutritional supplements for diseased trees. Similarly, sizable financial resources are currently being devoted to explore new alternatives including genetic modification of citrus trees, search for resistant varieties, and the use of antibiotics for the treatment of diseased trees. However, it would be difficult to argue that any of these alternatives has proven more effective than the *T. radiata* mass rearing program at slowing the spread of HLB. In other words, the biological control program has been as effective—or as ineffective—as all other available alternatives in the fight against HLB.

In a scenario where biological control agents, including *T. radiata*, and other factors are helping reduce *D. citri* populations in organic and low-spray groves, this *D. citri* control service can be monetized as the difference between the pre-HLB spray cost of $523.67 and the post-HLB spray cost of $1244.77, or a total of $721.10 per hectare in implied pest control benefits. Using the 2616 hectares of organic citrus reported by USDA-ERS [43], the total pest suppression benefit offered by natural enemies of the Asian citrus psyllid in organic groves can be estimated at $1.88 million per year.

Another relevant comparison may be the amount of money that has been funneled for HLB-related research in recent years. A number of Federal and state agencies have awarded funds for HLB research including the USDA's HLB multi-agency coordination (MAC) group and the FL Department of Citrus. In fiscal years 2014 and 2015 alone, USDA MAC awarded a total of $11.8 million in research funding [41]. Similarly, the FL Department of Citrus, through the Citrus Research Development Foundation, committed nearly $6 million in fiscal year 2012–2013 for HLB research, and has invested over $37 million in HLB-related research since fiscal year 2007–2008 [7].

It is also clear that FL's mass rearing and release program for *T. radiata* has not been as successful as other biological control programs. However, FL's *T. radiata* program meets two of the three reference points of success for biological control initiatives outlined by Orr [30]. The first goal of a biological control program is to achieve establishment of the control agent, and only 34 % of programs achieved this goal [30]. In this aspect, FL's program has been a tremendous success, as the range of *T. radiata* in the state is as extensive as that of the Asian citrus psyllid. The second objective of biological control is to achieve some level of pest suppression, and FL's program has also been successful, joining the 42 % of biocontrol initiatives that have also achieved this goal [30]. The last objective, complete suppression of the target pest, was not achieved in our case. However, only 16 % of programs have achieved this mark [30].

The *T. radiata* mass rearing program in FL is largely funded by the federal government through the USDA-APHIS CHRP program. In fact, there are similar federally funded mass rearing programs in California and Texas using either or both *D. aligarhensis* and *T. radiata* as biological control agents. However, under the leadership of FDACS DPI, the state of FL has devoted most of this funding to improvements in human and physical capital, rather than simply to the mass rearing of parasitic wasps. Specifically, FL has used CHRP funds earmarked for Asian citrus psyllid biocontrol to develop new and improved processes for the rearing of other biological control agents and the construction of greenhouses and laboratories used for the mass rearing process in a highly controlled environment. Conversely, other states have used these funds to produce parasitoid wasps in less controlled field environments, such as in citrus trees covered by mesh nets. Therefore, regardless of the outcome of the biological control program, the state of FL has gained state-of-the-art facilities and know-how that can be used in future biological control programs.

One of the goals of this article was to help pave the way for meaningful research on the economics of HLB. Such research may include bioeconomic models of disease population dynamics of the *D. citri* vector, as well as its natural enemies. Spatially explicit modeling at the grove level may prove useful in formulating improved HLB management practices for conventional and non-conventional growers. Similarly, spatially explicit modeling at the regional level may help improve coordination and management at that scale through the CHMA's.

After nearly 10 years since the arrival of HLB in FL, it is becoming evident that a silver bullet against the disease will continue to elude citrus producers for the foreseeable future. Perhaps a wise strategy would be to develop a new management approach whose objective is not to eradicate or cure HLB, but to manage it and still maintain productive orchards. Such a strategy is likely to be based on integrated pest management principles and certainly will include several of the practices currently available, but this will also require producers to change some of the tactics currently being used to manage HLB. It is very likely that biological control, either through the mass rearing or through the conservation of native and introduced natural enemies of the Asian citrus psyllid, will be a part of such a broad strategy.

Acknowledgments We thank Norm Leppla, Muhammad Haseeb and the participants at the 2015 Southern Agricultural Economics Association annual meetings for useful comments and suggestions. This project has been funded in part by the USDA Animal and Plant Health Inspection Service (APHIS), Plant Protection and Quarantine (PPQ) Program.

References

1. Adams D, Keenan R, Olexa M, McGovern R, Cossey J (2007) The legal basis for regulatory control of invasive citrus pests in Florida: a review of the citrus canker and spreading decline cases. Drake J Agric Law 12:409–422
2. Arakawa K, Mivamolo K (2007) Flight ability of Asiatic citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae), measured by a flight mill. Res Bull Plant Prot Serv Jpn 43:23–26
3. Bove J (2006) Huanglongbing: a destructive, newly-emerging, century-old disease of citrus. J Plant Pathol 88:7–37
4. Dewdney M, Roberts P, Graham J, Chung K, Zekri M (2001) Homeowner fact sheet: citrus canker. UF-IFAS, Gainesville
5. Farnsworth D, Grogan K, van Bruggen A, Moss C (2014) The potential economic cost and response to greening in Florida citrus. Choices 29:1–6
6. Florida Department of Agriculture and Consumer Services, United States Department of Agriculture-NASS (2015) Florida Citrus Statistics. USDA, Maitland
7. Florida Department of Citrus (2013) Florida department of citrus 2012–2013 annual report. Florida Department of Citrus, Bartow
8. Gottwald T, Graham J, Irey M, McCollum T, Wood B (2012) Inconsequential effect of nutritional treatments on huanglongbing control, fruit quality, bacterial titer and disease progress. Crop Prot 36:73–82
9. Grafton-Cardwell E, Stelinski L, Stansly P (2013) Biology and management of Asian citrus psyllid, vector of huanglongbing pathogens. Annu Rev Entomol 58:413–432
10. Halbert S, Manjunath K (2004) Asian citrus psyllids and greening disease of citrus: a literature review and assessment of risk in Florida. Fla Entomol 87:330–353
11. Halbert S, Manjunath K, Roka F, Brodie M (2008) Huanglongbing (citrus greening) in Florida. In: Proceedings of FFTC-PPRI-NIFTS joint workshop on management of citrus greening and virus diseases for the rehabilitation of citrus industry in the ASPAC, Hanoi, Vietnam, pp 58–67
12. Halbert S, Niblett CL, Manjunath KL, Lee RF, Brown LG (2002) Establishment of two new vectors of citrus pathogens in Florida. In: Proceedings of international society of citriculture IX congress, pp 1016–1017
13. Hall DG (2010) Biology, history and world status of *Diaphorina citri*. North American Plant Protection Organization. In: Proceedings of the second taller Internacional Sobre Huanglongbing y el Psilido Asiatico de los Citricos, pp 8–36
14. Hall DG, Gottwald TR (2011) Pest management practices aimed at curtailing citrus huanglongbing disease. Outlooks Pest Manag 22:189–192
15. Hall D, Richardson M, Ammar E, Halbert S (2013) Asian citrus psyllid, *Diaphorina citri*, vector of citrus huanglongbing disease. Entomol Exp Appl 146:207–223
16. Hodges A, Spreen T (2012) Economic impacts of citrus greening (HLB) in Florida, 2006/07–2010/11. UF IFAS, Gainesville
17. Hung TH, Hung SC, Chen CN, Hsu MH, Su HJ (2004) Detection by PCR of *Candidatus* Liberibacter asiaticus, the bacterium causing citrus huanglongbing in vector psyllid: application to the study of vector pathogen relationship. Plant Pathol 53:96–102
18. Inoue H, Ohnishi J, Ito T, Tomimura K, Miyara S (2009) Enhanced proliferation and efficient transmission of *Candidatus* Liberibacter asiaticus by adult *Diaphorina citri* after acquisition feeding in the nymphal stage. Ann Appl Biol 155:29–36
19. Jones M, Stansly P, Russo J (2013) Extension model to improve Asian citrus psyllid control in citrus health management areas (CHMAs). Proc Fla State Hort Soc 126(2013):1–4
20. Kerr C, Leppla N, Rohrig E, Lotz G, Stuart R, Smith T (2014) Mass-rearing *Tamarixia radiata* standard operating procedures. FDACS-DPI, Gainesville
21. Liu YH, Tsai JH (2000) Effects of temperature and life table parameters of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae). Ann Appl Biol 13:201–206
22. Mann RS, Ali JG, Hermann SL, Tiwari S, Pelz-Stelinski K (2012) Induced release of a plant-defense volatile “deceptively” attracts insect vectors to plants infected with a bacterial pathogen. PLoS Pathog 8(3):e1002610
23. Michaud J (2004) Natural mortality of Asian citrus psyllid (Homoptera: Psyllidae) in central Florida. Biol Control 29:260–269
24. Moss C, Grogan K, Farnsworth D, van Bruggen A (2014) The economic cost of Huanglongbing (citrus greening) to Florida’s orange industry: estimates of producer and consumer surplus. UF Food and Resource Economics Department, Gainesville
25. Muraro R (2004) Summary of the 2003–2004 citrus budget for the Central Florida (ridge) production region. UF-IFAS, Lake Alfred
26. Muraro R (2004) Summary of the 2003–2004 citrus budgets for the Southwest Florida production region. UF-IFAS, Lake Alfred
27. Muraro R (2012) Summary of 2011–2012 citrus budget for the Southwest Florida production region. UF-IFAS, Lake Alfred
28. Muraro R (2012) Summary of the 2011–2012 citrus budgets for the Central Florida (ridge) production region. UF-IFAS, Lake Alfred
29. National Research Council (2010) Strategic planning for the Florida citrus industry: addressing citrus greening disease. National Academy of Sciences, Washington
30. Orr D (2009) Biological control and integrated pest management. In: Peshin R, Dhawan A (eds) Integrated pest management: innovation-development process. Springer, Dordrecht, pp 207–239
31. Pelz-Stelinski KS (2011) Vector-pathogen interactions: transmission of *Candidatus* Liberibacter asiaticus and its effect on Asian citrus psyllid life history. In: Second annual citrus health research forum, 4–6 October, Denver CO
32. Pelz-Stelinski KS, Brlansky HR, Ebert TA, Rogers ME (2010) Transmission parameters for *Candidatus* Liberibacter asiaticus by Asian citrus psyllid. J Econ Entomol 103:1531–1541
33. Qureshi J, Rogers M, Hall D, Stansly P (2009) Incidence of invasive *Diaphorina citri* (Hemiptera:Psyllidae) and its introduced parasitoid *Tamarixia radiata* (Hymenoptera: Eulophidae) in Florida citrus. J Econ Entomol 102:247–256
34. Richards T, Shanafelt D, Fenichel E (2013) Foreclosures and invasive insect spread: the case of Asian citrus psyllid. Am J Agric Econ 96:615–630
35. Rohrig EA, Hall DG, Qureshi QA, Stansly PA (2012) Field release in Florida of *Diaphorencytrus aligarhensis* (Hymenoptera: Encyrtidae) an endoparasitoid of *Diaphorina citri*

(Homoptera: Psyllidae) from Mainland China. Fla Entomol 95:479–481

36. Roistacher CN (1996) The economics of living with citrus diseases: huanglongbing (greening) in Thailand. In: da Graça JV, Moreno P, Yokomi RK (eds) Proceedings of the 13th international conference of the international organization of citrus virologists (IOCV). University of California, Riverside, pp 249–285
37. Salifu A, Grogan K, Spreen T, Roka F (2012) The economics of the control strategies of HLB in Florida citrus. Proc Fla State Hort Soc 125:22–28
38. Singerman A, Useche P (2015) Impact of citrus greening on citrus operations in Florida. UF IFAS, Gainesville
39. Spann T, Atwood R, Dewdney M, Ebel R, Ehsani R, England G, Futch S, Gaver T, Hurner T, Oswalt C, Rogers M, Roka F, Ritenour M, Zekri M, Boman B, Chung KR, Danyluk M, Goodrich-Schneider R, Morgan K, Morris R, Muraro R, Roberts P, Rouse R, Schumann A, Stansly P, Stelinski L (2010) IFAS guidance for huanlongbing (greening) management. UF IFAS, Gainesville
40. Tiwari S, Mann R, Rogers M, Stelinski L (2011) Insecticide resistance in field populations of Asian citrus psyllid in Florida. Pest Manag Sci 67:1258–1268
41. United States Department of Agriculture (2015) Huanglongbing (HLB) multi-agency coordination updates. http://www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=hlb-mac-updates.xml. Accessed 8 Apr 2015
42. United States Department of Agriculture-APHIS, Florida Department of Agriculture and Consumer Services (2006) Citrus health response plan (CHRP) State of Florida. FDACS, Gainesville
43. United States Department of Agriculture-ERS (2013) Organic production. http://ers.usda.gov/Data-products/organic-production.aspx. Accessed 8 Apr 2015
44. Xu CF, Xia YH, Li KB, Ke C (1998) Further study of the transmission of citrus huanglongbing by a psyllid, *Diaphorina citri* Kuwayama. In: Timmer LW, Garnsey SM, Navarro L (eds) Proceedings of the 10th conference of the international organization of citrus virologists (IOCV). University of California, Riverside, pp 243–248