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Comparisons of economic thresholds for Asian citrus psyllid management suggest a revised approach to reduce management costs and improve yield

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Huanglongbing (HLB) or citrus greening disease is transmitted by the Asian citrus psyllid, *Diaphorina citri* Kuwayama. Vector control is considered a basic component of HLB management even under high disease incidence scenarios. While vector management heavily relies on the application of synthetic chemical sprays, overuse of insecticides raises several concerns including insecticide resistance, environmental impacts, and secondary pest outbreaks. The present study aims to compare the effects of three different economic thresholds (ET-0.2, 0.5, 1.0) and one calendar-based application schedule on the incidence of *D. citri* and beneficial species in plots of commercially grown citrus, as well as end-of-season yield and overall management costs. The results suggest that reducing spray frequency from eight to as few as three sprays per year had little effect on counts of pest and beneficial insects in the field. The numbers of *D. citri* and that of a secondary weevil pest were similar between plots treated with the calendar-based spray plots and plots managed with the ET-1.0. Furthermore, spider numbers were higher in the ET-1.0 plots, while ant numbers were lower compared with calendar sprayed plots. Management input costs were lower under economic thresholds (ET-0.5–ET-1.0) than with monthly calendar-based sprays, while yield losses were only slightly greater in the lower threshold of 0.2 mean psyllids per tap than with calendar sprays. Overall, management savings of more than 100% made up for this difference. Together, these results suggest that implementing a spray program of rotated chemistries based on an economic threshold of

0.5–1.0 adult psyllids per stem tap could provide both economic and ecological benefits. We discuss the implications of such an approach in the context of a young citrus tree protection program and the greater goals of sustainable citrus production under HLB.

KEYWORDS

citrus greening disease, Asian citrus psyllid (ACP), sustainable agriculture, economic threshold, rotational application, natural enemy, secondary pest

Introduction

Huanglongbing (HLB), or citrus greening is considered the world's most devastating citrus disease with no known cure (Bové, 2006). Disease management is mainly dependent on the control of the Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama (Chen et al., 2018, 2020), the insect vector that transmits the causal plant pathogen, *Candidatus* Liberibacter asiaticus (*C*Las). As a result, insecticide use has greatly intensified, and along with it, the concomitant risks for insecticide resistance, secondary pest outbreaks, and natural enemy declines in citrus agroecosystems (Zhang and Swinton, 2009; Monzo et al., 2014). Insecticide resistance for *D. citri*, among other specialty crop pests, is best managed through the implementation of properly rotated spray programs (Georghiou, 1983; Immaraju et al., 1990; Chen et al., 2006, 2021; Bielza et al., 2008). In addition to pest suppression, their ancillary goal is to relax the selection pressure of a single toxin with serial applications of different chemical classes (Crow, 1957). However, in addition to rotational considerations to maintain pests susceptible to insecticide, it is also important to incorporate economic thresholds (ETs) to reduce management costs and balance the non-target effects of insecticide applications on beneficial species (Qureshi and Kostyk, 2021). Consequently, insecticide strategies that maximize *D. citri* control while preserving profits and maintaining ecological stability are the goal of integrated pest management programs (Qureshi and Stansly, 2010).

There are several known predators of *D. citri* common in commercial citrus, including spiders (Araneae), predaceous arboreal ants (Hymenoptera: Formicidae, Pseudomycinae), ladybird beetles (Coleoptera: Coccinellidae), and lacewings (Neuroptera: Chysopidae) (Qureshi and Stansly, 2009; Monzo and Stansly, 2017). The risks of an insecticide application to natural enemies depend on the active ingredient, targeted guild, or species (Amalin et al., 2000; Pekár, 2002; Ragsdale et al., 2007), but generally, biological control efficacy declines as insecticide spray frequency increases. For this reason, we became interested in whether the implementation of different economic thresholds impacted natural enemies in the field. However, increased spray frequency is also associated with secondary pest outbreaks, such as with *Panonychus citri* (Trombidiformes: Tetranychidae), in citrus (Zanardi et al., 2018). The Sri Lankan weevil, *Myllocerus undecimpustulatus* Faust (Coleoptera: Curculionidae), is an invasive, polyphagous pest in Florida with the potential to spread throughout the southern U.S. Furthermore, several subspecies of *M. undecimpustulatus* are considered pests on citrus in Southern Florida since 1993 and more recently in Broward County, Florida in 2000 (George et al., 2015), and Nassau County, Florida in 2013 (Neal, 2013). Adult *M. undecimpustulatus* feed on leaves, causing the typical leaf notching produced by many broad-nosed weevils. More selective spray applications in citrus may help reduce the frequency and severity of secondary pests as natural enemy populations increase and the likelihood of non-target resistance effects decreases (Qureshi and Stansly, 2009; Monzo and Stansly, 2017).

Economic thresholds are used to trigger pest management decisions (Stern et al., 1959; Headley, 1972) and represent pest infestation levels at which the application cost equals that of damage prevented by the application (Plant, 1986). During the initial 15 years of the HLB epidemic in Florida, the use of an economic threshold for *D. citri* was considered unfeasible, given that a single inoculation was thought to be sufficient to infect a tree with a potentially tree-killing pathogen (Pelz-Stelinski et al., 2010) and initial efforts were focused on preventing the spread of disease (Grafton-Cardwell et al., 2013). Calendar-based insecticide sprays were implemented in an area-wide management program in which local growers coordinated their spray activity (Rogers et al., 2011). While attention was given to insecticide resistance and a rotation schedule was implemented, economic thresholds were not adopted. We now know that although inoculation frequency is not related to pathogen load in the phloem, prolonged feeding by *D. citri* appears to stunt plant growth and decrease the salicylic acid-dependent immune response of citrus to the pathogen (Ibanez et al., 2019). Thus, tree defenses against *C*Las appear compromised if populations of *D. citri* are not adequately managed (Monzo and Stansly, 2017). Additionally, advances in disease management through foliar nutritional applications circumvent some of the vascular symptoms of HLB infection, extending the lifespan of infected trees and the window during which sustainable vector management is needed (Stansly et al., 2014). However, more recent data suggest that adopting an economic threshold can also improve yields and profits, even in heavily infected citrus groves (Monzo and Stansly, 2017).

HLB is widespread across Florida, and it is commonly assumed that nearly 100% of *D. citri* or citrus trees are currently carrying the pathogen (Coy and Stelinski, 2015; Monzo and Stansly, 2017; Ibanez et al., 2020; Chen et al., 2021). The conventional approach dictated that more frequent sprays, combined with the elimination of infected trees, effectively reduced HLB expansion (Belasque et al., 2010). A longitudinal investigation of psyllid-pathogen-plant interactions indicated that prolonged and uninterrupted exposure to *D. citri* feeding suppresses plant immunity and inhibits growth (Ibanez et al., 2020), which may explain measurable yield gain in groves where vector suppression is still practiced despite 100% infection of trees (Monzo and Stansly, 2017). However, while HLB progresses more rapidly in plots without insecticide management, long-term assessments of HLB transmission in Florida have shown that the disease also eventually spreads into areas implementing monthly sprays (Ibanez et al., 2019). Under these conditions, growers question whether continued vector management provides benefits given the economic losses already incurred by the epidemic. Economic thresholds can be established based on vector density or the degree of pathogen infection. They may be influenced by many factors, including vector resistance, variety, rootstock, climate, and other agroecosystem properties (Chen et al., 2018). As a result, the economic threshold for citrus can differ by area and even require adjustment within the same orchard (Monzó and Stansly, 2020; Chen et al., 2021). In Florida, where HLB is endemic, it might be possible to reduce the number of required chemical applications for *D. citri* based on the implementation of economic thresholds ranging from 0.5 to 1.0 adult psyllids per tap (Chen et al., 2021). This could reduce the number of insecticide applications from 12 to between 4 and 6 times per year while maintaining equivalent yields. However, the exact threshold within this range has not yet been defined and may differ based on cultivar and tree age (Plant, 1986; Chen et al., 2022).

In the present study, we investigated the potential of implementing economic thresholds to increase the sustainability of *D. citri* management in citrus under conditions of high HLB incidence. This is critical as we move toward the overall goal of balancing pest suppression with management costs and non-target effects on the larger agroecosystem within citrus affected by HLB. Specifically, we measured the incidence of *D. citri* in plots managed with either of three economic thresholds as compared with those treated using calendar sprays, and related *D. citri* densities to cost of application and yield. Moreover, a mode of action (MoA) rotation was incorporated with these thresholds to combine IPM practices. After these programs were initiated, we quantified the effect of these thresholds on (1) *D. citri* incidence, (2) natural enemy populations, (3) prevalence of secondary pests, and 4) fruit quality and yield per hectare over one year. Using these data, we then estimated the cost savings associated with a revised management program incorporating an economic threshold.

Materials and methods

Insecticides

We applied commercial formulations of insecticides approved for *D. citri* management in Florida citrus including: Dimethoate 4E (dimethoate 43.5%), Agri Flex (abamectin 3% + thiamethoxam 13.9%), Admire Pro 4.6F (imidacloprid), Danitol 2.4 EC (fenpropathrin 30.9%), Micromite 80 WGS (diflubenzuron), Exirel (cyantraniliprole), and Delegate WG (spinetoram) representing different insecticide classes (Table 1). Insecticides were diluted in 451.61 L of water at maximal label rates and applied using a 500 gal airblast sprayer (Rears Manufacturing, Monaco RV LLC, Coburg, OR USA) that delivered 247 gal per hectare (ha).

Experimental design

A year-long experiment was initiated in the spring of 2021 in a sweet orange (*Citrus sinensis* L. Osbeck) var "Hamlin" grove under standard agricultural practices for citrus, including mowing and fertilization, located in Lake Alfred, Florida (N: 28°03'84 9"; W: 81°42'47"; Supplementary Figure 1). Trees were planted ∼3 m apart with 6 m between rows and were 5–6 years old at the time of the study, with an estimated initial HLB infection level of 100% (Supplementary Table 1). Three economic threshold treatments were compared: 0.2, 0.5, or 1.0 adults per stem tap with a non-threshold-based calendar application. The spray treatments were arranged in a randomized complete block design with four replicate plots per treatment. Each plot consisted of six rows of 10 trees (60 trees total). There was a buffer zone of ∼20 trees between replicates.

Economic threshold determinations

The economic threshold value was calculated as the mean number of adults per tap from 20 randomly selected trees per plot (Monzo and Stansly, 2017). If the mean reached or exceeded the target economic threshold, all replicate plots assigned to that treatment threshold were sprayed. If the mean *D. citri* density for a threshold treatment was within ± 0.05 per tap below the target threshold, a decision was often made to spray that treatment rather than waiting until the following week. An insecticide program was designed to maintain *D. citri* numbers as close to zero as possible with rotation implemented to mitigate resistance development. Using our threshold values, the number of total insecticide

TABLE 1 Insecticides evaluated with various economic threshold treatments for suppression of *Diaphorina citri*.

Insecticide Trade name	Active Ingredient	Chemical class	Preharvest Interval (PHI) in days	EPA register number	Mode of Action[a]	IRAC Group
Dimethoate 4E	Dimethoate	Organophosphate	15–45	66330-223	AChE inhibitor	1B
Micromite 80 WGS	Diflubenzuron	Benzoylureas	2	400-487	Inhibitors of chitin biosynthesis type 0	15
Danitol 2.4 EC	Fenpropathrin	Pyrethroid	1	59369-35	SDC modulators	3A
Actara WG	Thiamethoxam	Neonicotinoid	0	100-938	nAChR Competitive modulators	4A
Exirel	Cyantraniliprole	Diamide	1	279-9615	Ryanodine receptor modulators	28
Delegate WG	Spinetoram	Spinosyn	1	62719-541	nAChR allosteric modulators	5
Agri-flex	Abamectin + Thiamethoxam	Avermectins + Neonicotinoid	7	100-1350	GluCl allosteric modulators +nAChR competitive modulators	6 + 4A

[a], AChE: acetylcholinesterase; nAChR, Nicotinic acetylcholine receptor; SDC, sodium channel; GluCl, Glutamate-gated chloride channel.

TABLE 2 Description of the insecticide rotations used in the economic threshold (ET) treatments evaluated for management of *Diaphorina citri* in the field.

App Date	Treatment			
	ET-0.2*	ET-0.5	ET-1.0	Calendar+
March 16, 2021	Fenpropathrin	Fenpropathrin	Fenpropathrin	Fenpropathrin
May 12, 2021	Dimethoate	–	–	Dimethoate
June 12, 2021	Fenpropathrin	–	–	Fenpropathrin
July 10, 2021	Cyantraniliprole	Dimethoate	Dimethoate	Cyantraniliprole
August 4, 2021	Thiamethoxam	Cyantraniliprole	–	Thiamethoxam
September 10, 2021	–	–	–	Spinetoram
September 29, 2021	Spinetoram	Thiamethoxams	Cyantraniliprole	Diflubenzuron
November 3, 2021	Difubenzuron	–	–	Abamectin

*ET-0.2, ET-0.5, ET-1.0 were based on the mean number of adults per tree tap.
+Calendar refers to the calendar-based spray treatment.

applications varied by treatment. Seven applications were made for the 0.2 adults per tap threshold treatment; four applications were made for the 0.5 adults per tap threshold treatment; three applications for the 1.0 adult per tap threshold treatment; and eight applications for calendar treatment (Table 2).

Pest and natural enemy assessment

We sampled pests and natural enemies 28 times every 7–15 d, beginning on March 5, 2021 and ending on November 8, 2021. To collect *D. citri*, a 22 × 28 cm white plastic sheet was held horizontally about 30 cm underneath a randomly chosen branch, which was then struck sharply three times with a 40 cm length of PVC pipe. Adult *D. citri* falling on the sheet were quickly counted (Monzo et al., 2014). Additionally, all other arthropods that dropped on the card were counted. These included spiders (Araneae), arboreal ants (Hymenoptera: Formicidae, Pseudomyrecinae), ladybird beetles (Coleoptera: Coccinellidae), and lacewings predators (Neuroptera: Chrysopidae), which were previously identified as key natural enemies of *D. citri* in Florida citrus (Xiao et al., 2007; Qureshi and Stansly, 2009). We also quantified the presence of a potential secondary pest in citrus, the Sri Lankan weevil, *M. undecimpustulatus*.

Harvest and yield evaluation

Marketable fruit was harvested on December 19, 2021, in experimental plots. Because trees were at a pre-production stage of maturation, yield, and fruit quality estimates for each plot were conducted based on a subsample of three trees per treatment plot selected at random. We harvested all the fruit from each tree and counted the total number per tree. We then recorded fruit weight from a sub-sample of five fruit per tree selected at random. To estimate how the different spray threshold treatments affected profits, we combined the management costs per hectare with the estimated yield losses per hectare due to HLB. As the economic threshold decreases, spray frequency, and management costs increase. Insecticide costs were compiled from the University of Florida extension reports and the 2020–2021 Florida Citrus Production Guide. All prices were based on the product used or the closest comparable products. To estimate the potential cost savings of eliminating a single insecticide application, we used a range of field sizes and insecticide prices based on observed values. The average retail price of representative insecticides registered for use in citrus and their associated application costs were compiled from University of Florida extension reports. Average fruit prices ($2.7 USD per kg of solids) were estimated using data obtained from the National Agriculture Statistical Service (NASS, 2020). Yield losses, expressed as USD per hectare, caused by *D. citri* and associated with each simulation was obtained using the equation proposed by Monzo and Stansly (2017) for groves under high HLB incidence. The equation relates the cumulative number of adult *D. citri* (K season) with the yield losses caused by the presence of this pest:

$$C = p \times 2014.5 \times (\frac{(3.39 \times Kseason}{1 + \frac{3.39 \times Kseason}{21.8}})/100$$

where, C is the monetary value expressed in $/ha associated with the yield loss resulting from the seasonal number of vectors during Kseason and where, P is the orange juice price paid at the harvest, expressed in $/kg of solids.

Statistical analysis

Statistical analysis of arthropod counts in the field was conducted using R version 4.1.3 "One Push-Up." We used linear mixed-effects models with the package "lme4" to compare the counts of each taxonomic group of insects based on ET treatment. Due to large positive skew and zero-inflation, the data were log10 +1 transformed. The plot number (replication) and date were nested, random factors due to variation in baseline counts between plots and seasonal effects on abundance. Pairwise *post-hoc* comparisons were conducted using the package "emmeans." Harvest and yield evaluations were also analyzed with linear mixed models although the data were not transformed as the residuals were normal. Because there were no differences in fruit number and weight, *post-hoc* assessments were not conducted.

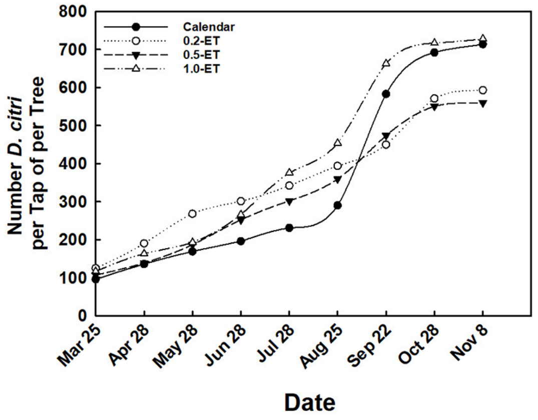

FIGURE 1
Cumulative number of *Diaphorina citri* under various economic threshold (ET) treatments in Florida citrus during 2021.

Results

Pest and natural enemy assessment

Arthropod counts in the field varied significantly by economic threshold (ET) treatment for *D. citri* (Figure 1), the secondary pest *M. undecimpustulatus* (Supplementary Figure 2), spiders (Figure 2A), predaceous arboreal ants (Figure 2B), and lacewings (Figure 2C), but not for ladybird beetles, which were similar across all treatment plots (Figure 2D; Table 3). However, the pattern associated with those differences varied by taxa (Table 4). Among *D. citri*, the greatest infestation was found in the Calendar and ET-1.0 treatments, while the lowest was found in the ET-0.2 and ET-0.5 treatments. The opposite trend was observed for *M. undecimpustulatus*, with a greater infestation in the ET-0.2 and ET-0.5 treatments compared to the Calendar and ET-1.0 plots. For spiders, reduced spray frequency in the ET-1.0 and ET-0.5 plots was associated with the greatest number of spiders, whereas ant numbers were lowest in the ET-1.0 plots. No lacewings were found in the Calendar or ET-1.0 plots, but similar numbers were found in the other treatments.

Harvest and yield evaluation

Due to the decrease in the number of spray applications, the total management costs of the lowest threshold treatment (ET-0.2) were estimated at $451.50 per ha and decreased as the threshold increased. Costs were greatest in the calendar-based spray treatment, as this was associated with the greatest number of sprays. Yield estimates did not reveal statistically significant differences in the number of fruits harvested in plots with varying spray frequency (Figure 3A). Similarly, there were no

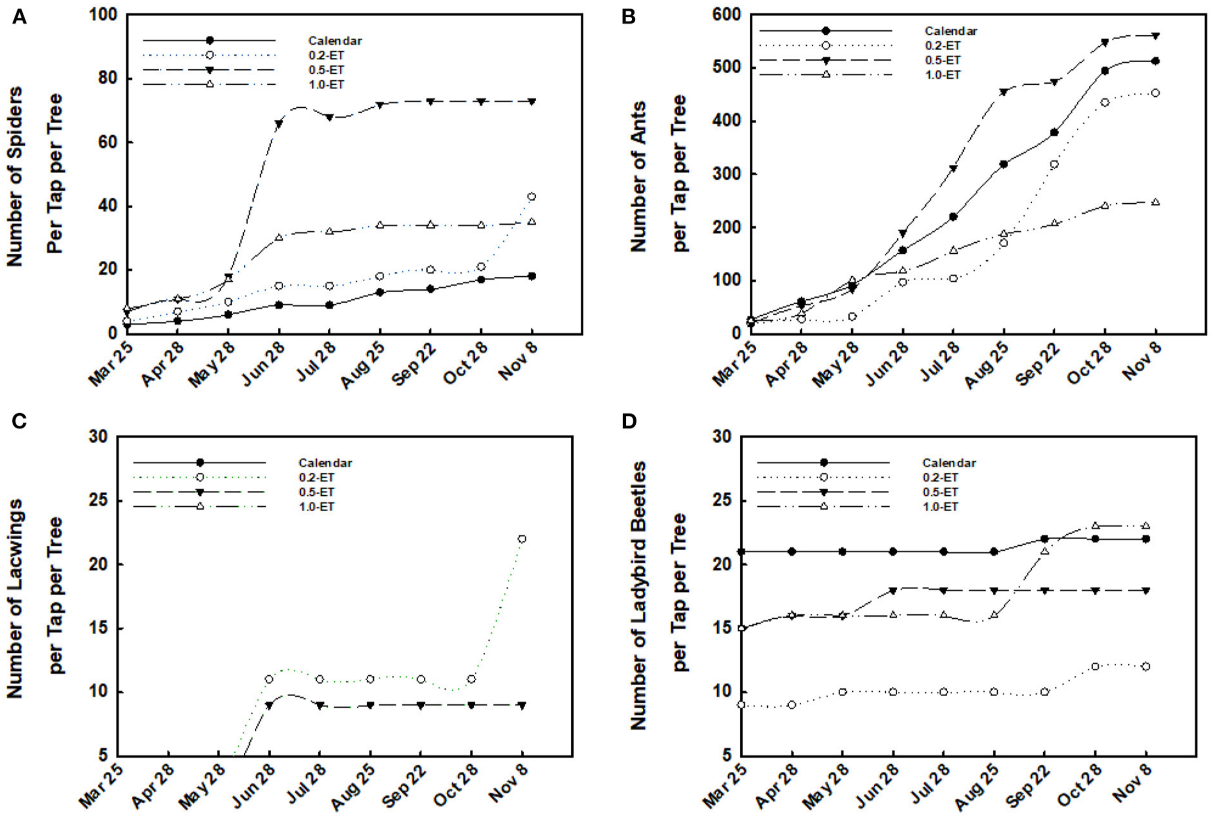

FIGURE 2
The cumulative number of natural enemies including spiders **(A)**, ants **(B)**, lacewings **(C)**, and ladybird beetles **(D)** observed in Florida citrus groves in the different economic threshold (ET) treatments during 2021.

TABLE 3 Effects of four different economic threshold treatments on *Diaphorina citri*, natural enemies, and secondary pests in Florida citrus.

Pest and Beneficial insects	Sum sq	Mean sq	*df*	*F*-value	*p* > *F*
D. citri	0.417	0.139	3, 8852.3	6.61	<0.001
M. undecimpustulatus	0.007	0.002	3, 8888.7	3.76	0.01
Spiders (Araneae sp.)	0.025	0.008	3, 8862.3	5.41	0.001
Predaceous arboreal ants (Pseudomycinae sp.)	1.496	0.499	3, 8858.3	28.39	<0.001
Lacewings (Chrysopidae sp.)	0.003	0.001	3, 8853.8	5.42	0.001
Ladybird beetles (Coccinellidae sp.)	0.002	0.001	3, 8856.7	1.17	0.32

differences in the average weight per tree (Figure 3B). Although differences in fruit yield were not statistically different, we did observe the greatest number of marketable fruits in the calendar-based spray plots (Mean = 32.75 ± 8.02), while the lowest was in the ET-0.5 plots (Mean = 14.42 ± 3.26). Using those observed values, when we estimated overall losses due to herbivore damage, we found that losses were lower under the economic threshold approach, but only when *D. citri* numbers were low. For this reason, we found that yield loss was actually greatest in the calendar-based treatment, followed by 1.0-ET, 0.5-ET, and 0.2-ET. However, when we considered the combined total losses associated with each spray treatment, we found that management cost savings associated with the higher ET treatments compensated for small declines in yield associated with elevated *D. citri* infestation (Table 5; Supplementary Tables 2–4).

Discussion

Implementation of thresholds as treatment guidelines for *D. citri* is essential for transitioning away from calendar-based

TABLE 4 Differences in overall mean arthropod count ± SE and statistical significance (indicated by different letters in columns) between ET treatment groups within each arthropod category (Tukey LSD: α = 0.05).

Pest and Beneficial insets	Calendar	ET-0.2	ET-0.5	ET-1.0
D. citri	0.32 ± 0.02 (ab)	0.26 ± 0.01 (bc)	0.25 ± 0.01 (c)	0.33 ± 0.02 (a)
M. undecimpustulatus	0.004 ± 0.001 (b)	0.007 ± 0.002 (ab)	0.012 ± 0.003 (a)	0.004 ± 0.001 (b)
Araneae	0.008 ± 0.002 (b)	0.009 ± 0.002 (b)	0.016 ± 0.003 (ab)	0.03 ± 0.01 (a)
Formicidae	0.23 ± 0.01 (ab)	0.21 ± 0.02 (b)	0.26 ± 0.02 (a)	0.11 ± 0.01 (c)
Chrysopidae	–[a]	0.005 ± 0.002 (a)	0.004 ± 0.002 (a)	–
Coccinellidae	0.01 ± 0.002 (a)	0.006 ± 0.002 (a)	0.008 ± 0.002 (a)	0.01 ± 0.002 (a)

[a] Indicates zero counts for this organism.

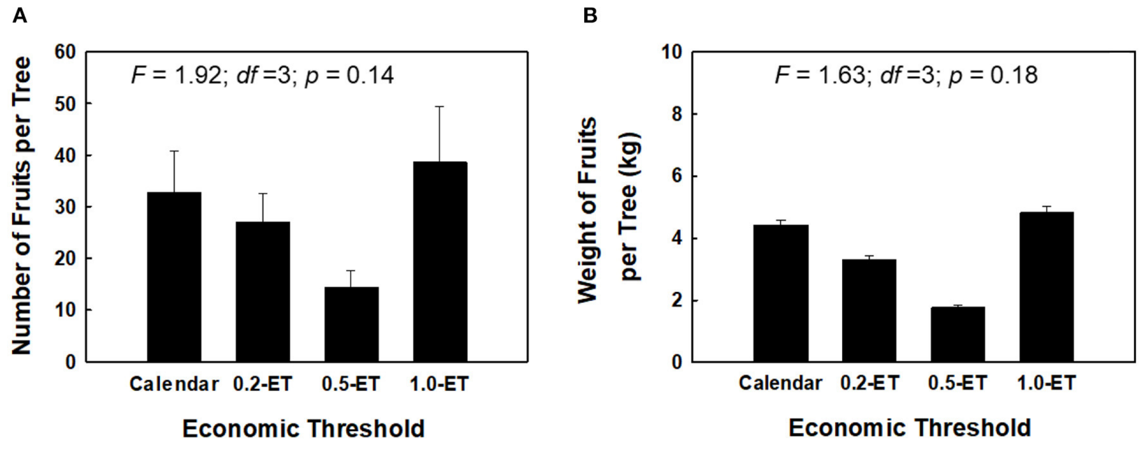

FIGURE 3
Comparative yield **(A)** and citrus fruit quality **(B)** following end-of-season harvest during December 2021.

TABLE 5 Estimated management costs ($/ha) and yield losses ($/ha) associated with the presence of *Diaphorina citri* in Florida citrus.

Management Approach	Initial *D. citri*	No. Insecticide sprays	K season[a]	Management costs ($/ha)	Estimated Yield loss ($/ha)[b]	Total losses ($/ha)
Calendar	43	8	714	487.22	271.48	758.70
ET-0.2	53	7	593	451.50	206.24	657.74
ET-0.5	35	4	560	229.0	212.79	441.79
ET-1.0	48	3	728	166.92	236.18	403.09

[a] Cumulative number of D. citri for the year.
[b] Due to herbivore damage.

sprays and developing sustainable citrus management programs. Our results indicate that an economic threshold ranging between 0.5 and 1.0 psyllids can effectively predict the need for *D. citri* treatment application in young citrus trees without substantial losses due to decreased management intensity. Counts of *D. citri* in grove plots managed with fewer sprays triggered by the 1.0 ET were similar to numbers found in those managed with conventional calendar-based sprays. Further, yield declines associated with more *D. citri* were compensated economically by savings associated with fewer sprays. Our study also assessed the impacts of the various economic threshold treatments on natural enemies and secondary pests in citrus. One year of an intensive insecticide program for *D. citri* management resulted in a reduction in natural enemy abundance and some cases a modification of seasonal patterns of some key predator groups. The results obtained in this study may underestimate the negative consequences of insecticides on beneficial arthropods over the long term but highlight how fewer and more selective insecticide applications during critical periods could favor overall *D. citri* management. While the regular application of insecticides to control *D. citri* significantly suppressed the vector population, it also affected non-target beneficial species. Indeed, our data demonstrated reduced spider counts in the plots treated with greater spray frequency. However, this effect was less clear for lacewings, ants, and coccinellids. At a minimum, our results suggest that there are benefits to reducing spray frequency, although it may take additional measures to improve predator biodiversity and retention in commercial citrus.

This is the first study of this size in young citrus to demonstrate that overall profits would not be compromised following an economic threshold-based program. While yield losses associated with greater *D. citri* pest pressure were elevated in higher economic threshold treatments (1.0 ET), decreased management costs more than compensated for this outcome. Further, our study revealed the greatest overall yield losses in the calendar-based treatment, showing how yield effects associated with *D. citri* infestation are complex and even monthly sprays do not fully eliminate the losses due to this pest under the stress of HLB disease. Thus, commercially acceptable yield could be generated with fewer insecticide sprays following an action threshold-based program using a 0.5–1.0 economic threshold range, saving money, time, and benefiting the environment. This is consistent with the findings of Monzo and Stansly (2017), who demonstrated that an economic threshold for *D. citri* could be useful under circumstances of near-complete HLB infection. Specifically, by using a threshold of 0.5 psyllids per tap to trigger the need for a spray, the investigators reduced the number of annual treatments per year from eight in a calendar year compared to only four sprays in the threshold-based treatment and achieved returns that were either equivalent or better than those which were seen in the calendar-based treatment. Together these results show that the investment made in psyllid control costs using a calendar-based program may not be justified when disease incidence is high.

Threshold-based management for *D. citri* would likely be limited to groves where HLB infection is endemic and occurs at a high frequency per crop area. This management approach would not be effective in preventing the spread of disease given that a certain background population of a phytopathogen vector is deemed allowable. Instead, the goal should be to minimize injury associated with psyllid feeding to already infected trees, to prevent compromises in tree defense responses, which occur after sustained psyllid feeding injury (Ibanez et al., 2019). Young trees have greater potential value than older counterparts but are also more susceptible to HLB infection because they produce a new leaf flush more frequently (Monzo and Stansly, 2017). New leaf flush is highly attractive to *D. citri* adults (Monzo and Stansly, 2017; Ibanez et al., 2020; Chen et al., 2021) and is the sole location of egg-laying and nymph development (Wenninger et al., 2009). This may explain the more rapid resurgence of psyllid populations in areas treated with the 0.2 psyllids/tap threshold in this investigation conducted in young trees, than in the investigation conducted by Monzo and Stansly (2017) in mature orchards. Therefore, it is likely that maintenance of relatively low *D. citri* populations in young trees (5–6 yr old) will require greater input of insecticides and therefore lower treatment thresholds than what would be required in older trees. Nonetheless, even a relatively conservative treatment threshold, such as an average of 0.2 psyllids per sample, would significantly decrease the cost of production. The additional potential ecological benefits of such a program and their contribution to the economics of growing citrus, such as gains in pest suppression services from beneficial insects, remain to be quantified in greater detail in future investigations.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

XC and HG collected the data. XC and DS compiled and analyzed the data. All authors edited the manuscripts and contributed ideas to study design.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.948278/full#supplementary-material

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