Mining Value from ACP Prevalence Data

Neil McRoberts, Rick Dunn and Holly Deniston-Sheets

Project Summary

The Asian citrus psyllid (ACP) has spread throughout southern California since 2008, when it was first detected in the state. While it is now established in many southern counties, these areas have varying levels of ACP infestations. To gain a better understanding of annual population dynamics, possible environmental differences between counties in southern California and possible reasons for those patterns, we examined five years of ACP population data in California from 2015 through 2019. Our conclusions will be used to evaluate the effectiveness of employed control strategies, as well as guide proactive protective measures in the future.

Since the California citrus industry is undertaking some of the most ambitious and costly efforts to suppress huanglongbing (HLB) in the world, it is important to evaluate the effectiveness of these efforts and put data collected by the Citrus Pest and Disease Prevention Division (CPDPD) trapping program to good use. We report here on early results from an on-going DATOC project to support the CPDPD in its efforts to suppress the spread of HLB in California.

The incidence of HLB appears to be increasing more slowly in California than it has in other citrus-growing regions, but it is unclear how much of that difference can be attributed to control efforts and how much to other factors, such as climate effects on ACP populations. California's citrus is grown in a variety of climatic conditions in 23 counties; Riverside County alone, for example, contains six different climatic groups (according to the Köppen climate classification). This variation is much greater than in other areas of the world where ACP has spread and HLB incidence increased. The entire state of Florida, by comparison, contains only four climatic zones (Prism 2020). In addition to questions about climate variability, California's overall climate is more Mediterranean than most places ACP have invaded previously, so it remains unclear how well ACP are suited to the conditions encountered here. Determining the extent of these effects on ACP population dynamics will help us quantify the success of the regulatory control program, as well as determine how we can reallocate program resources for optimal success.

A key component in the analysis was CPDPD commercial grove trapping data for four counties – Imperial, Riverside, San Bernardino and Ventura – from 2015-19, and for San Diego from 2016-19. Much of the CPDPD's activity and data collection are focused in residential areas. The trapping data from commercial citrus have rarely been included in the analysis for program support. Our work is, therefore, expanding the value provided to the CPDPD from this piece of the program. Although trapping data can be difficult to interpret, previous research has shown that psyllids are moderately attracted to yellow panel traps, and trap catches fluctuate in sync with ACP populations that are observed by tap sampling (Hall et al. 2007).

The CPDPD trapping program was restructured in 2016, and the number of traps in Southern California was reduced. Every month since then, about 50 traps have been checked in San Diego, 60 in Imperial, 70 in San Bernardino, 80 in Riverside and 200 in Ventura. In total, the analyses presented here used data from nearly 75,000 trap reports. These grove traps are currently placed at one per square mile, but not all commercial citrus acreage is covered (**Figure 1**).

Weather data were compiled from the California Irrigation Management Information System (CIMIS) and the National Oceanic and Atmospheric Administration (NOAA) National

Climatic Data Center for the same timeframes and locations as the trapping data. Citrus flush patterns from residential grapefruit, lemon, lime, orange, tangelo and tangerine trees were extracted from data provided by David Morgan, Ph.D., of the California Department of Food and Agriculture (CDFA) Biological Control Program (**Figure 2**). These data were collected in the same counties as the ACP data and in approximately the same time frame. Weather and ACP data from Riverside were split into two categories (designated as “west” and “east”) based on a distinct climatic difference.

The time series data for the traps confirm that there are stable differences in ACP populations between southern California counties (**Figure 3**). ACP prevalence is highest in San Diego, where more than 50 percent of traps routinely catch ACP year-round, and lowest in Imperial and eastern Riverside, where populations are mainly detected in March and April, but many traps catch no ACP at all. In western Riverside, San Bernardino and Ventura, prevalence is variable, but spring and fall peaks generally can be seen in April and November with year-to-year variation.

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This type of work is an important preliminary step to be able to ascribe relative importance to the environment and the program activities in determining ACP population prevalence, which in turn will help determine how growers and the industry can respond to those expected levels of prevalence. As this project progresses, we will continue to use statistical analyses to match the patterns of ACP prevalence to weather data. The next steps are to include the effects of historic levels of grower coordination in area-wide insecticide applications on county-wide ACP populations and to correlate trap data with nymph and tap-sampling data collected by a Huanglongbing Multi-agency Coordination Group project. As this project draws to a close, its conclusions will be used to project expected patterns of ACP prevalence in different areas of southern California and the San Joaquin Valley if ACP were to become established there. These projections will help guide proactive protective measures for California citrus.

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References

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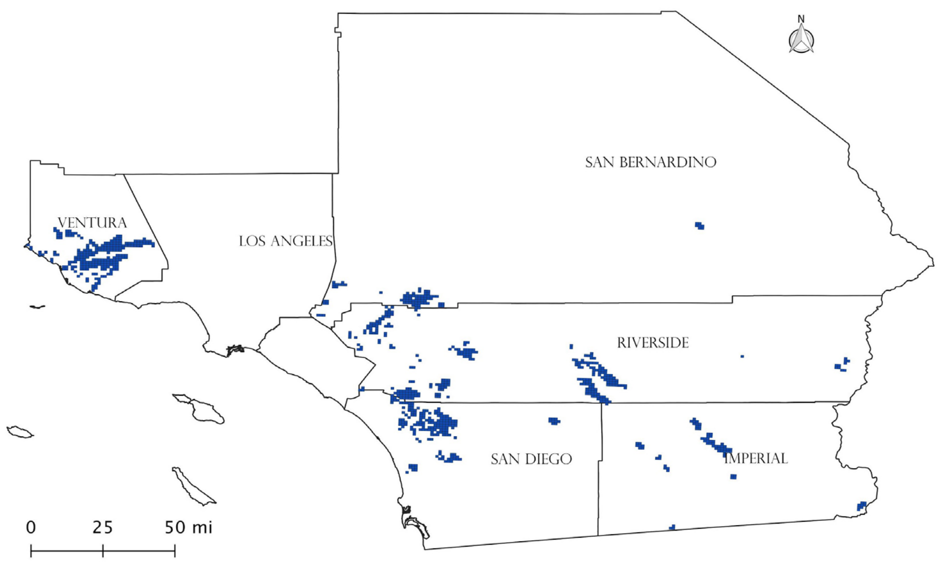

Figure 1. An example of trap locations used in this analysis (to a one square mile resolution): locations from traps collected in 2019 in the southern California counties examined in this analysis. Trap locations between 2015-18 were similar to those depicted in 2019.

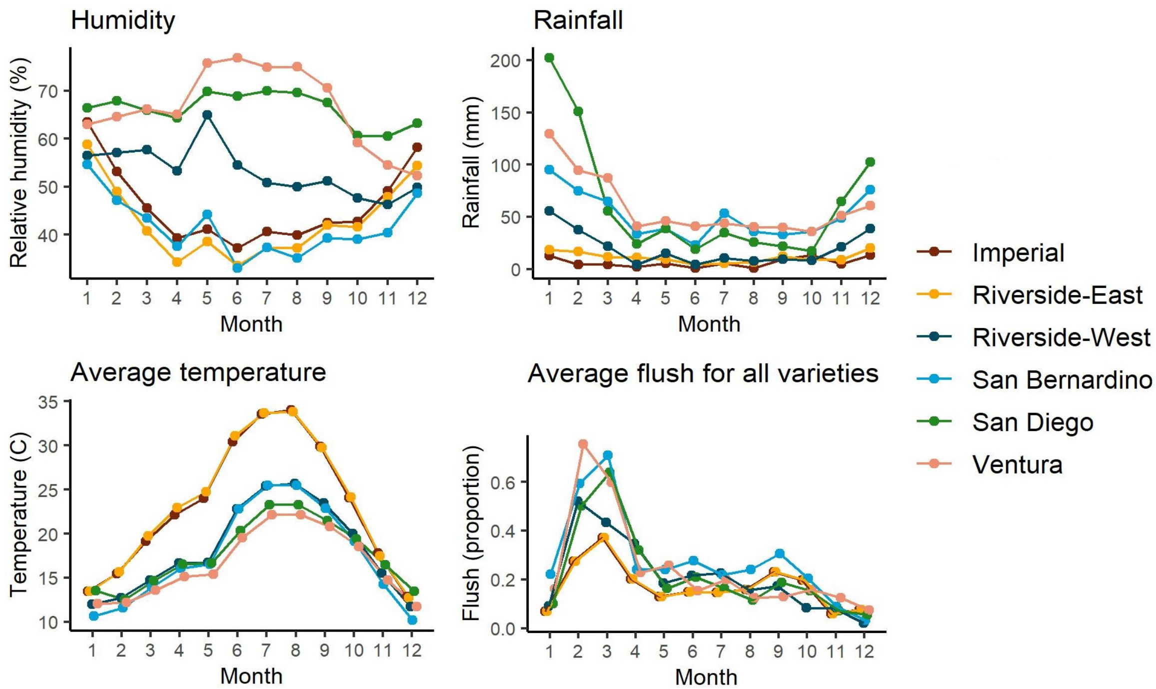

Figure 2. Average monthly climatic conditions from 2015-19 and flush patterns for the southern California counties examined in this project.

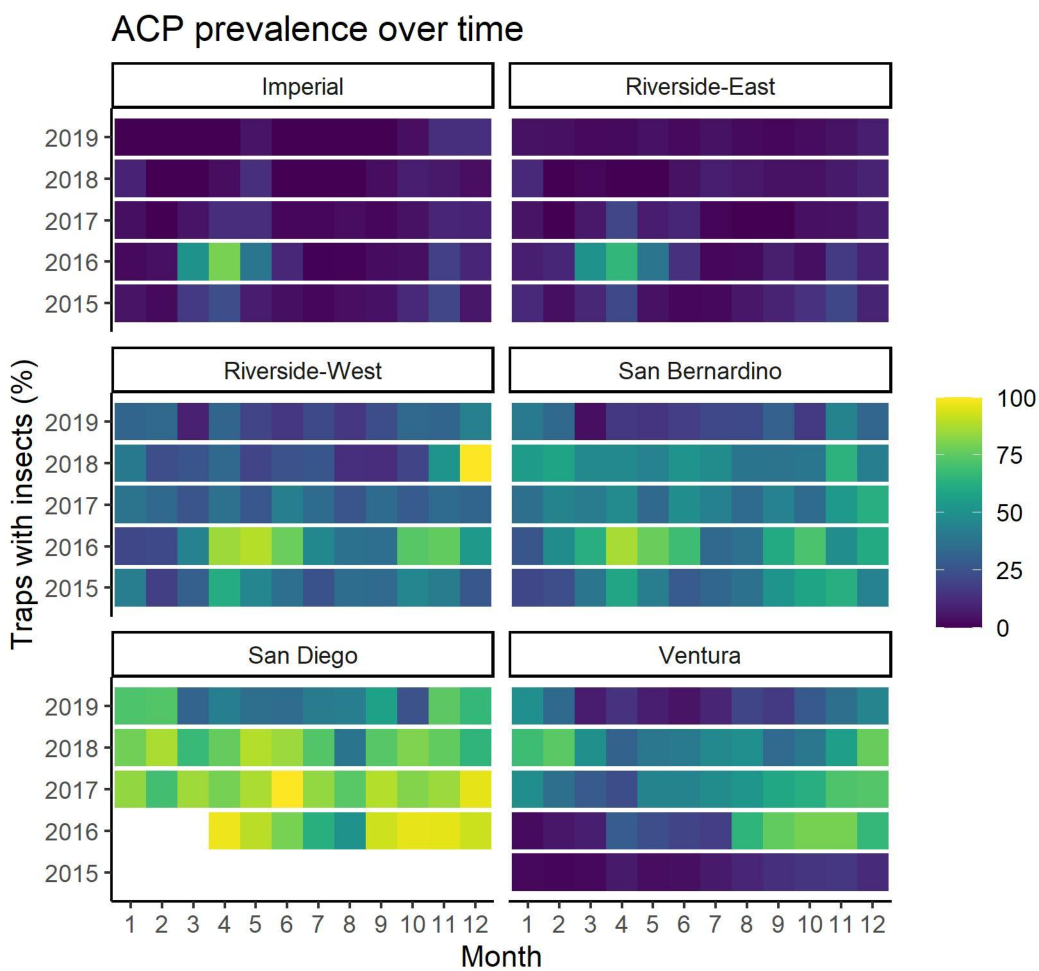

Figure 3. Monthly prevalence of Asian citrus psyllid from traps in five counties of southern California between 2015-19 (data only available in San Diego since 2016). Each row is a year and each column is a month within that year. The fill color indicates the percent of deployed traps that caught ACP that month. Data courtesy of the Citrus Pest and Disease Prevention Division.

Citrus Tarping Requirements Reduce ACP Movement

Neil McRoberts and Holly Deniston-Sheets

The Citrus Pest and Disease Prevention Committee (CPDPC) strives to make decisions that balance safeguarding the citrus industry from huanglongbing (HLB) with the resulting additional costs and work incurred by HLB mitigation efforts. One difficult decision came in 2017 when the CPDPC voted to impose tarping requirements on trucks moving bulk citrus. To determine if tarping has influenced Asian citrus psyllid (ACP) movement, the Data Analysis and Tactical Operations Center (DATOC) was asked to review ACP detections close to highways. The results strongly support tarping.

The San Joaquin Valley (SJV) contains more than 70 percent of California's packinghouses, and coastal and southern California counties ship more than 63 million pounds of bulk citrus into the SJV annually for processing, according to data provided by the California Department of Food and Agriculture **(Figure 1)**. This equates to 1,400 – 1,750 trucks, each one delivering 40-50 900-pound bins. An unfortunate consequence of this movement is "hitchhikers" – ACP that travel on harvested fruit to new areas. Because ACP can spread '*Candidatus* Liberibacter asiaticus.' the bacterium associated with HLB, the CPDPC implemented policies to address this issue, including a new requirement in 2017 that bulk citrus must be completely enclosed during transportation. It was important to determine the policy's effectiveness after implementation, since using tarps to enclose shipments is costly and potentially risky for workers.

DATOC examined ACP monitoring data collected by the Citrus Pest and Disease Prevention Division's trapping program. The data examined were limited to traps within five miles of major transportation routes as previous analyses from Florida indicated areas of high risk were on either side of transport routes (Gottwald 2013). Roads that connect packinghouses to major thoroughfares also were included. There was a clear, statistically significant reduction in the rate of ACP detection in the SJV that started when tarping regulations were enacted **(Figure 2)**. This implies that tarping is accomplishing its intended goal of reducing ACP movement out of southern California **(Figure 3)**.

CRB Research Project #5300-182

References

Gottwald, T.R. 2013. Risk-based residential HLB/ACP survey for California, Texas and Arizona. [Presentation] Retrieved August 31, 2020, from *http://www.plantmanagementnetwork.org/edcenter/seminars/outreach/Citrus/HLB/*

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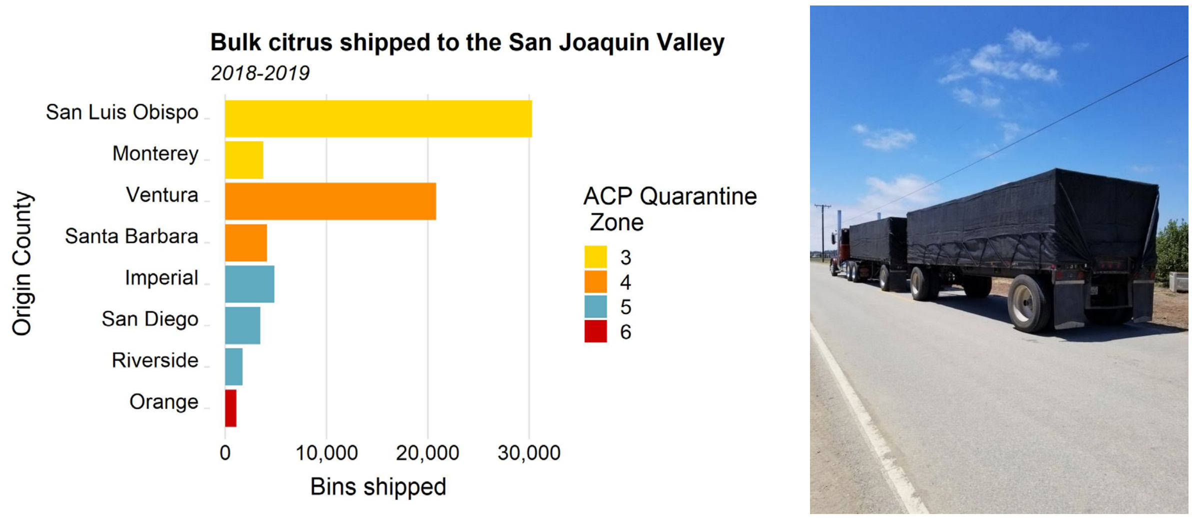

Figure 1. *Left: The volume of citrus fruit (as 900 lb. field bins) moved into the San Joaquin Valley from other ACP quarantine zones during the 2018-19 growing season. Data provided by the California Department of Food and Agriculture. Right: Typical truckload of 48 bins, with compliant tarping - tight and down to truck bed. Photo credit, Chris Sayer, Petty Ranch, Ventura County, California.*

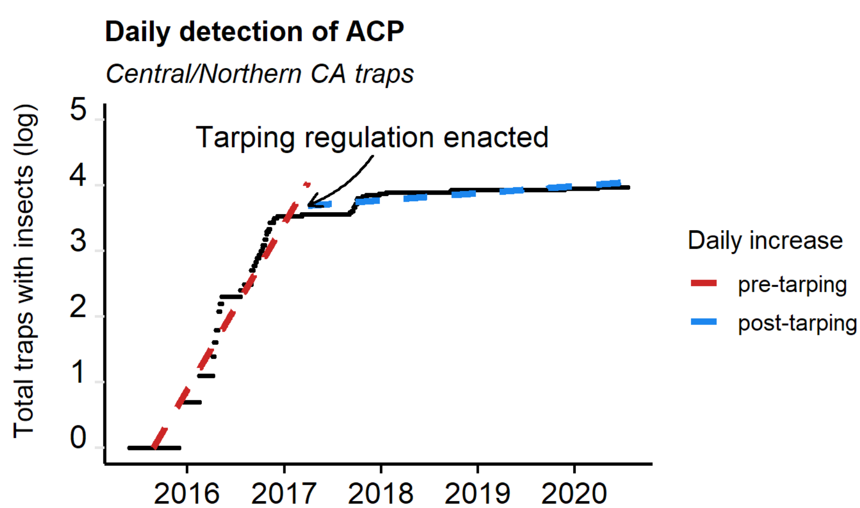

Figure 2. *The daily increase of ACP detections (black line) on yellow sticky traps within five miles of transportation corridors, pre- and post-tarping regulations. Red and blue dashed lines indicate the average increase in cumulative ACP detections from a linear model using time and the period (pre- or post-tarping) as predictors. The cumulative numbers showed exponential growth, so the daily average increase was found by fitting a linear regression to the natural log (log_e) of the data.*

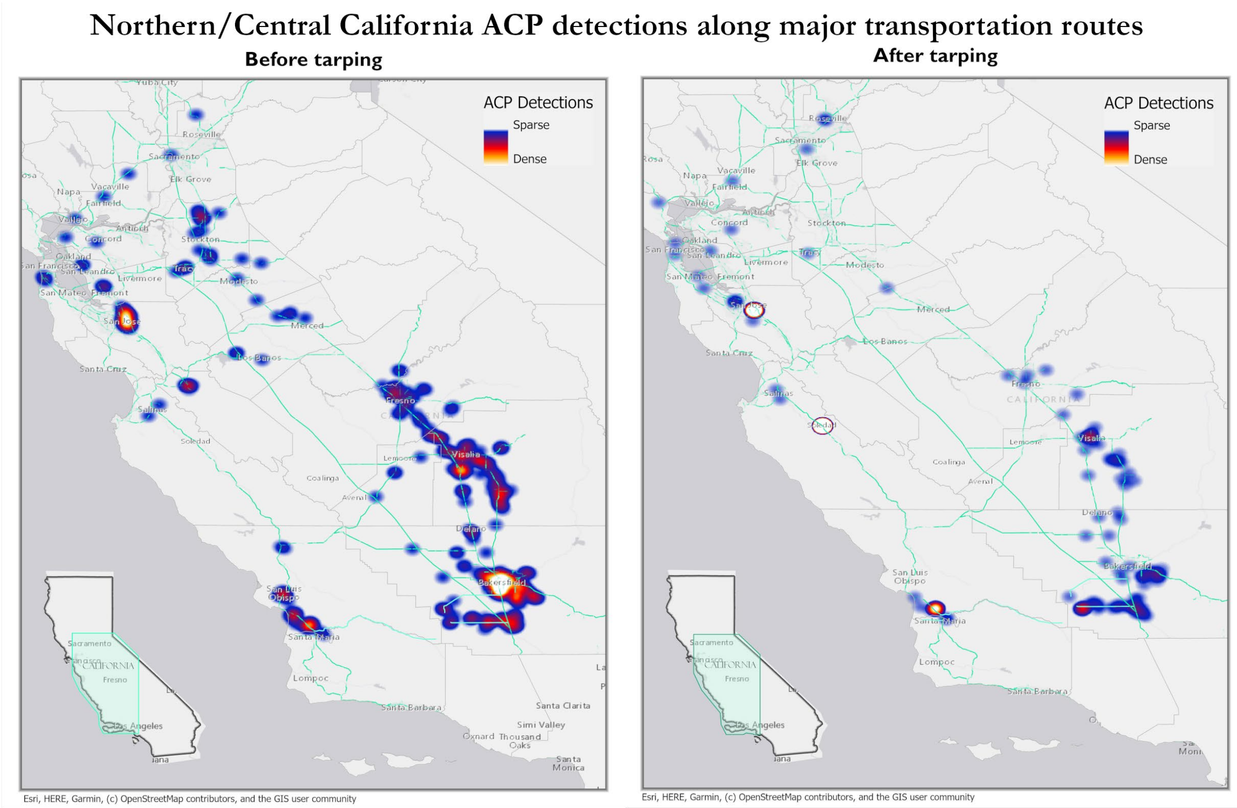

Figure 3. *The density of ACP detections on yellow sticky traps within five miles of major transportation routes in northern and central California before (left) and after (right) the tarping regulations were implemented. "Before tarping" data collected from January 2015 through March 2017. "After tarping" data collected from April 2017 - July 2020.*

Modeling the effectiveness of California's efforts to contain Huanglongbing

Neil McRoberts[1]
Holly Deniston-Sheets[2]
[1]*Quantitative Biology & Epidemiology Lab, Plant Pathology Dept., UC Davis*
[2]*Citrus Research Board*

Summary

One of the most complicated issues facing the Citrus Pest and Disease Prevention Committee (CPDPC) is how to quantify the effectiveness of the residential control program in protecting commercial groves from Huanglongbing, as it is difficult to establish what would have happened if the program had never been implemented (a counterfactual situation). Although there is no perfect way to discern the answers, the best option available is to use a model, with care, backed up with expert evaluation of the results. This is the approach we have used over the last year, refining an agent-based model (ABM) for Huanglongbing (HLB) spread. Preliminary work with a second spatially explicit model, the Cambridge model, has also been completed.

Results from the ABM indicate that a residential control program near commercial groves, structured like the one currently utilized in Southern California, significantly limits disease incursion into commercial groves from residential areas, especially when combined with an area-wide Asian Citrus Psyllid (ACP) management program in commercial citrus. Results from the Cambridge model also indicate that tree removal and ACP management limit HLB spread.

INTRODUCTION

The ABM, built by the epidemiology team at the USDA-ARS lab in Ft. Pierce, FL, has been applied to study two main groups of California landscapes: San Gabriel and Ventura County. Within Ventura, we have simulated the impacts of different configurations of the disease management program, in complement with a project funded by the Citrus Research Board which is evaluating the potential economic benefits of cooperation among growers.

Work on the Cambridge SEIR (Susceptible, Exposed, Infected, Removed) model is underway in collaboration with Dr. David Bartels (USDA-APHIS) and Prof. Christopher Gilligan (Cambridge University, UK) to give the program an additional set of projections for the development of HLB across a larger swath of California, using a model they developed and used for Texas. This additional work is being supported by a Plant Protection Act (Sec. 7721) award to UC Davis/Cambridge and APHIS.

Background

Agent-based model

Previous simulations with the agent-based model indicated that residential control programs consisting of HLB+ tree removal combined with insecticide applications limited disease spread in the city of San Gabriel. However, that work left unanswered questions about how limiting residential infections would ultimately affect commercial citrus production. To address this, we used the ABM to simulate the spread of HLB from residential infections into commercial groves in three areas of Ventura County: Las Posas, Ojai, and the Santa Clara Valley (Figure 1). Scenarios simulated a 20-year timeframe.

Three scenarios were completed with the ABM. Two used HLB/ACP control programs designed to mimic strategies currently utilized by CDFA and California growers as closely as possible within the inherent limitations of the model; one of these applied control in residential areas only, and the other in both residential and commercial areas. The third scenario implemented no control program. Each scenario was replicated 100 times, with the residential HLB introduction location randomized for each replication.

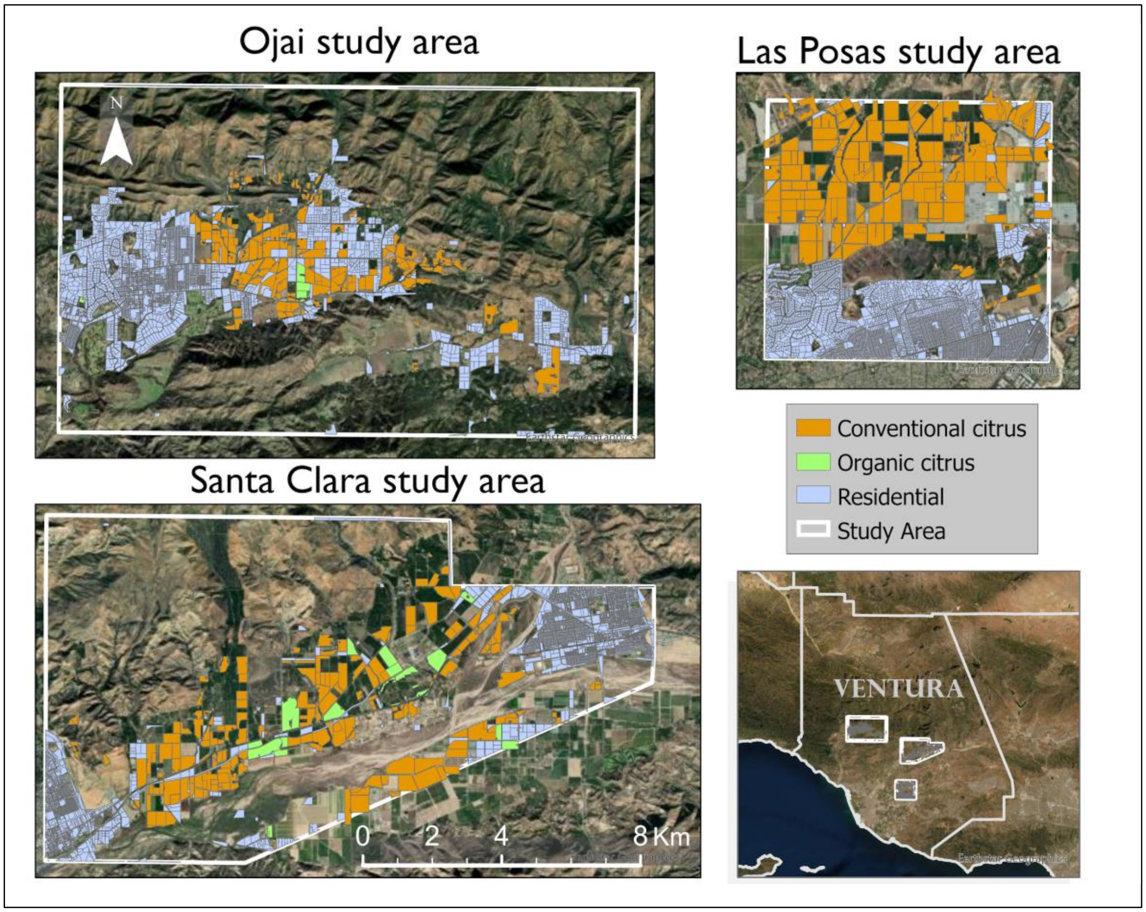

Figure 1. The three study areas in Ventura county used in the agent-based model. Orange polygons indicate the location of conventional citrus groves, green indicates organic groves, and purple are residential locations.

Residential

Under the "Residential" control program, a risk-based survey is implemented four times per year, surveying 25% of residential properties, with a 50% sampling density per property. Huanglongbing confirmations occur two weeks after the survey. Within seven days of confirmation, an insecticide spray with 90% efficacy is applied in a 50 m radius around any detected HLB+ trees, and a 250 m survey around the detection is implemented. Any subsequent HLB+ trees detected are removed, but no additional insecticide applications are made, regardless of additional detections.

Residential & Commercial

Scenarios implementing both residential and commercial control utilized the same control strategies detailed above, with the addition of commercial insecticide sprays. These sprays mimicked the current area-wide strategy in Ventura, with an insecticide applied once each during Jan-Feb, Jul-Aug, and Sep-Oct. All groves were treated within 21 days. The insecticide was assigned a 50% efficacy level as a compromise between high efficacy achieved by some growers and the low level of control obtained in other cases.

Cambridge model

The Cambridge model simulated HLB spread in Southern California (Figure 2) over 6 years, from 2015 - 2021. Two scenarios are presented here: HLB+ tree removal with ACP management, or no control. A 400 m treatment radius around HLB+ trees was assumed in these simulations. Treatments are assumed to reduce HLB transmissibility by 80%.

Figure 2. The Southern California study area used in the Cambridge model.

Results

Agent-based model

The percent of commercial trees infected with HLB over time is shown in Figure 3, and in residential trees in Figure 4. There are contrasting results for commercial production in Ojai compared with the other two areas studied with the ABM; in the scenario where only residential controls are implemented, HLB is predicted to reach more than 50% of trees in Ojai after 20 years. In Las Posas and the Santa Clara valley, HLB incidence in commercial citrus is predicted to be approximately 2% and 3%, respectively, after 20 years (Table 1). Although these simulations assume initial infections were always in residential areas, the results reveal that the effect of landscape and the spatial mixing of residential and commercial citrus may have a stronger impact on the rate of disease spread than was previously appreciated. Disease spread is predicted to be comparatively rapid in Ojai because of the extent to which commercial and residential citrus are intermingled (Figure 1). Note, however, that even in Ojai, effective vector control in commercial citrus is predicted to keep disease incidence to <2% of trees after 20 years.

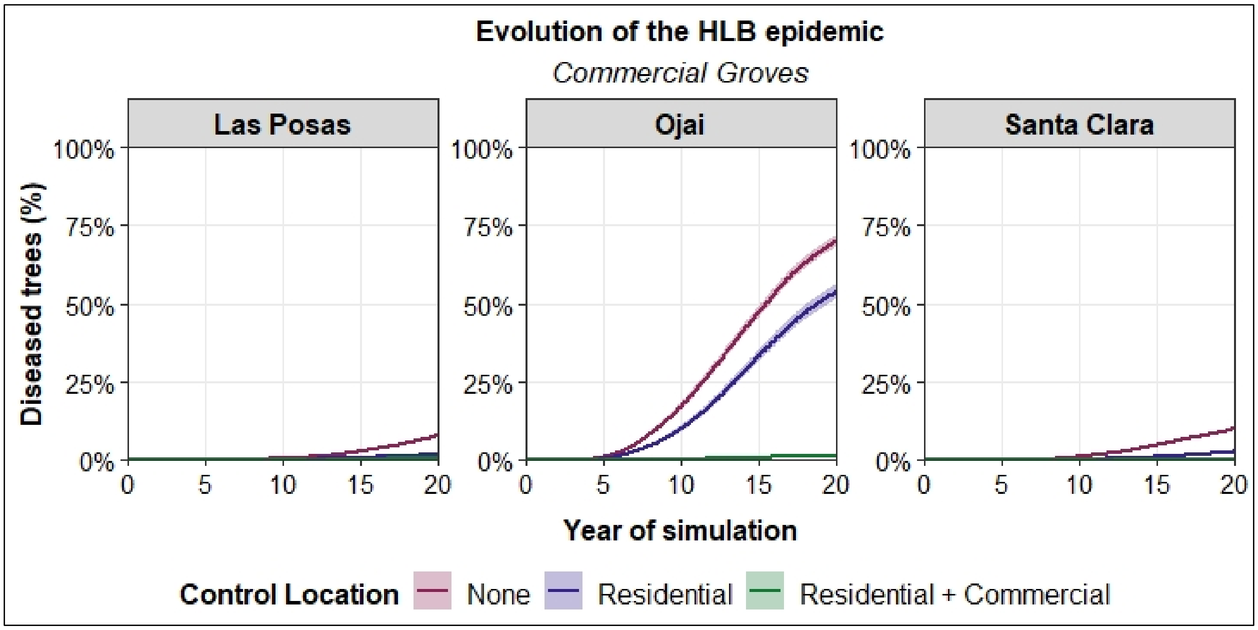

Figure 3. The percent of diseased trees in commercial groves in three study areas of Ventura county over 20 years under three different huanglongbing/ Asian citrus psyllid control programs.

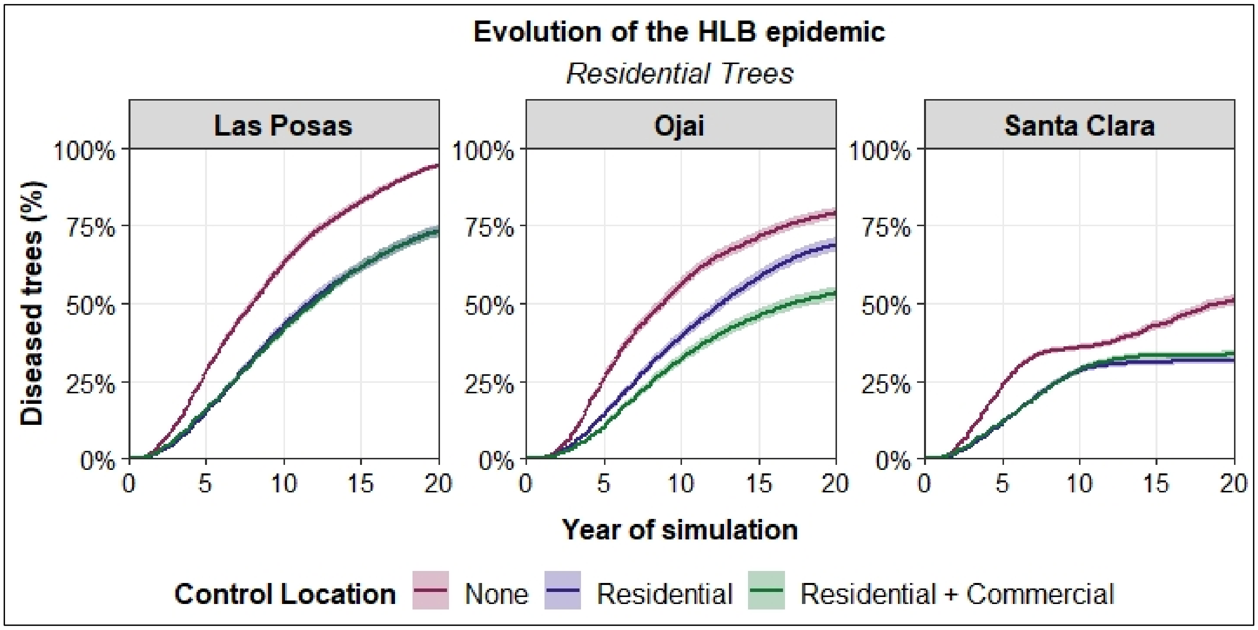

Figure 4 The percent of diseased trees in residential areas in three study areas of Ventura county over 20 years under three different huanglongbing/ Asian citrus psyllid control programs.

Table 1. Huanglongbing progress over five-year intervals from the simulated epidemics in Ventura County.

Las Posas Diseased Trees (%)						
	---------------------- Commercial ----------------------			---------------------- Residential ----------------------		
Year	**No Control**	**Residential**	**Residential + Commercial**	**No Control**	**Residential**	**Residential + Commercial**
5	0.09	0.04	0.02	28.25	15.01	15.70
10	0.63	0.29	0.17	62.90	42.77	41.38
15	2.80	0.86	0.37	82.77	61.65	61.65
20	7.85	1.87	0.70	94.34	73.24	72.98

Ojai Diseased Trees (%)						
	---------------------- Commercial ----------------------			---------------------- Residential ----------------------		
Year	**No Control**	**Residential**	**Residential + Commercial**	**No Control**	**Residential**	**Residential + Commercial**
5	1.07	0.56	0.04	26.06	14.40	10.42
10	17.35	10.20	0.31	56.41	39.48	32.18
15	47.32	33.47	0.90	71.37	58.38	45.95
20	69.83	53.77	1.48	78.96	68.80	53.22

Santa Clara Diseased Trees (%)						
	---------------------- Commercial ----------------------			---------------------- Residential ----------------------		
Year	**No Control**	**Residential**	**Residential + Commercial**	**No Control**	**Residential**	**Residential + Commercial**
5	0.07	0.04	0.01	23.45%	11.51	11.85
10	1.15	0.27	0.06	35.77	28.26	28.52
15	4.87	1.1	0.10	42.94	31.15	33.21
20	10.0	2.7	0.16	50.97	31.70	33.54

Cambridge model

Figure 5, below, shows the probability of infection on a logarithmic scale (blue = 0.001, red = approaching 1) in different stages of HLB progress for the LA basin and Riverside.

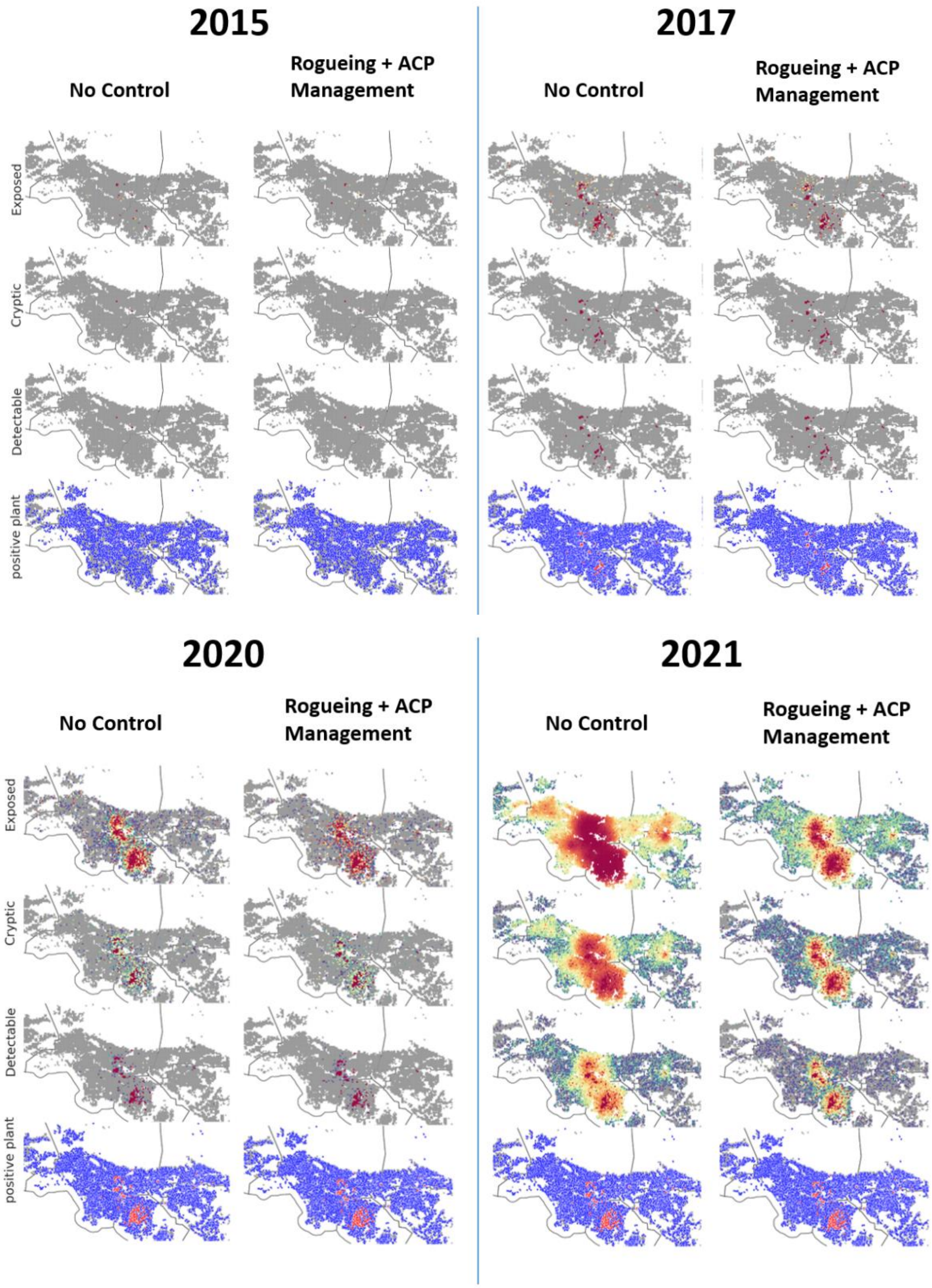

Figure 5. The probability of infection in different stages of HLB progress for the LA basin and Riverside. Probabilities are on a logarithmic scale (blue = 0.001, red = approaching 1). Figure provided courtesy of Cambridge University (Prof Chris Gilligan, Drs Viet Nguyen & Renata Retkute) and USDA-APHIS (Dr David Bartels).

Conclusions and future work

The purpose of this briefing is to provide an indication of the types of results that are being generated by the modeling studies. The results reported here indicate that ACP control around infected trees, with removal of known infected trees in residential areas, and in conjunction with ACP control in commercial citrus can significantly slow the rate of HLB spread into commercial citrus from residential sources.

The Cambridge model, which operates at a much larger spatial scale than the ABM but has less capacity for fine-tuning, is producing results that concur with observed experience and also with the annual risk-based survey risk calculation. We plan to get the two models running in tandem using a common set of parameters to simulate the effect of control activities with the aim of providing a more comprehensive analysis of the impact of the disease management program on the rate of spread of HLB.

While the results are encouraging, and further work will better match the structure of the simulated residential program to the set of activities used in reality, we stress that because the real program has evolved over time, simulations are always only an approximation of what is done in practice. We caution against hoping for nuanced answers about the effectiveness of fine details of program components; at a fine scale, the program may have to be evaluated simply on its merits.

Overall, we are encouraged by progress made, particularly over the last six months, and feel confident that the simulation modeling activities will be able to support the on-going deliberations about program cost-effectiveness by the Science Sub-Committee in 2021.

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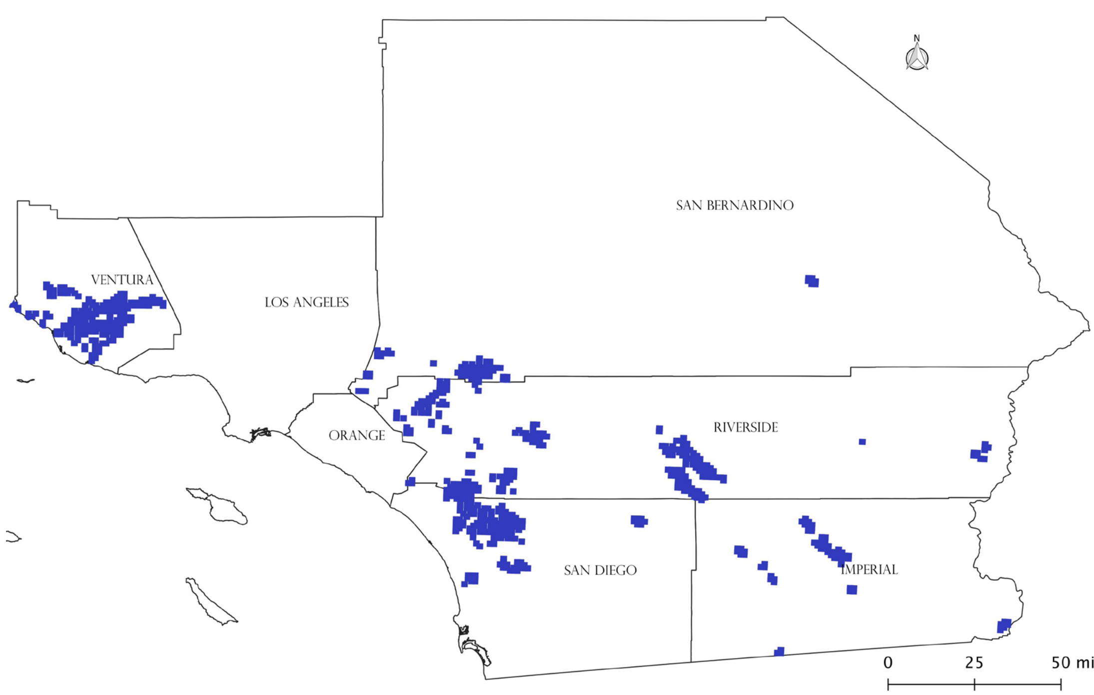

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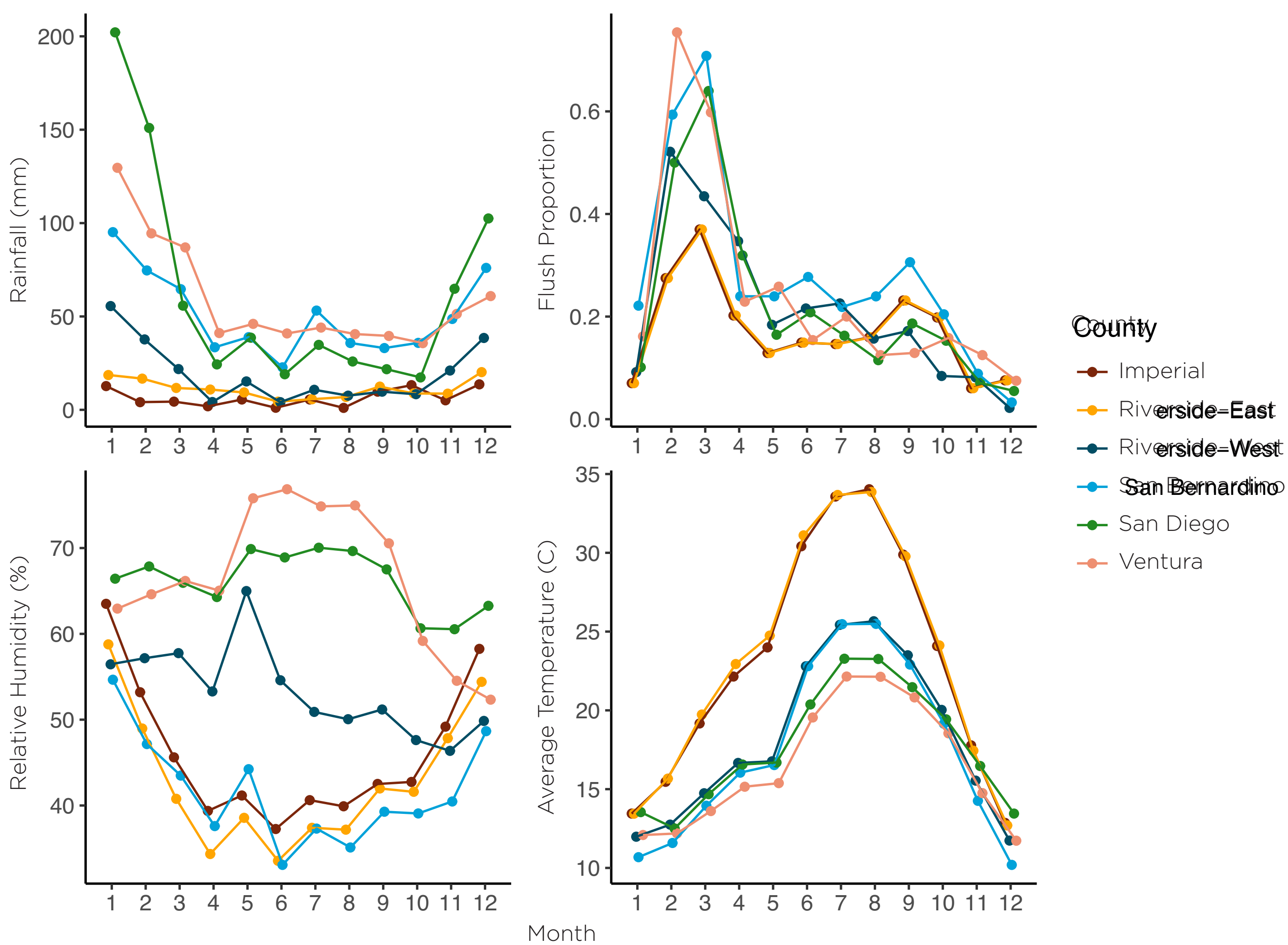

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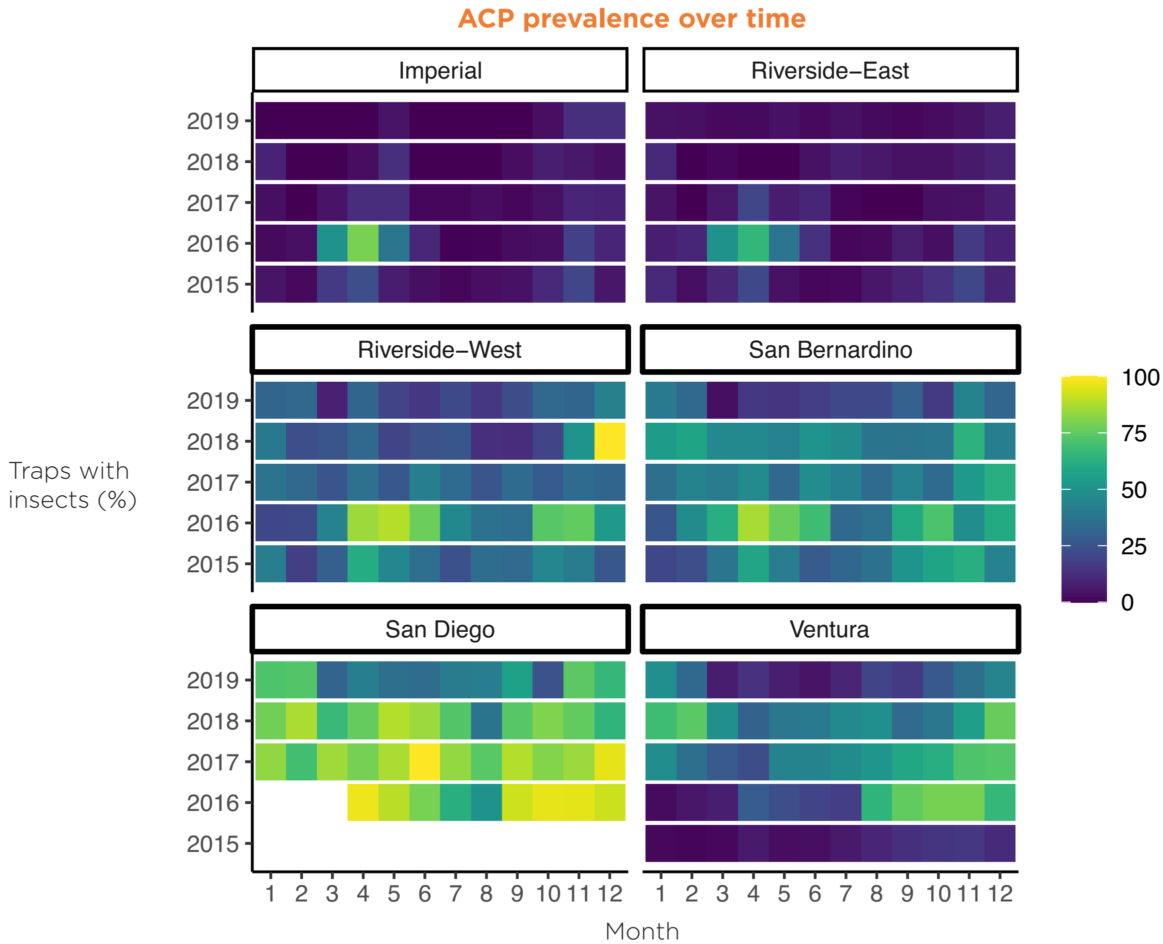

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OPTIMIZING RESIDENTIAL INSECTICIDE APPLICATIONS FOR COMMERCIAL GROVE PROTECTION

Holly Deniston-Sheets[1]
Monique Rivera[2]
Neil McRoberts[3]

[1]Citrus Research Board
[2]Department of Entomology, UC Riverside
[3]Quantitative Biology & Epidemiology Lab, Plant Pathology Dept., UC Davis

SUMMARY

DATOC was asked to explore how the procedure for applying insecticides in residential areas ("buffer zones") surrounding commercial groves under area-wide ACP control programs might be improved. We recommend that if the size of buffer zones must be reduced to optimize application timing and decrease spending, the zone be reduced to 250 m from 400 m; the area within 100 m from a grove should be treated first, followed by the remaining area out to the zone's outer edge at 250 m.

Background

Both the Science and Operations Subcommittees have dedicated an appreciable amount of time and effort to optimize the cost-effectiveness of recurring HLB and ACP management activities in Southern California. In this case, the Operations Subcommittee wanted to know how many houses would be included in buffer zones of varying sizes, how far into residential neighborhoods treatments would extend with a range of potential sizes, and what distance was considered large enough to offer protection to nearby commercial groves.

Evidence

To answer these questions, we examined buffer zones recently treated by CDFA, and compiled prior research on treatment efficacy and ACP flight patterns.

Buffer Zones

Maps of treated buffer zones demonstrate the broad range of neighborhood types, density, and grove sizes which are treated by CDFA. Newer home lots can be as small as 15 m x 15 m, but a typical suburban property is around 15 m x 30 m. Older homes are closer to 15 m x 46 m, and lots in affluent areas trend closer to 30 m x 56 m, or larger. Example Area 1 (Figure 1, left) shows a small grove surrounded by a relatively high-density neighborhood, with possible buffer zones of 100 m, 250 m, or 400 m indicated. In contrast, Example Area 2 (Figure 1, right) has far fewer residential properties around commercial groves and changing the size of the buffer zone here will likely make less significant differences in cost. Lastly, the residential area in Example Area 3 (Figure 2) has a similar housing density as Example Area 1, but as the grove is much larger, buffers in this area will contain many more properties (Table 1).

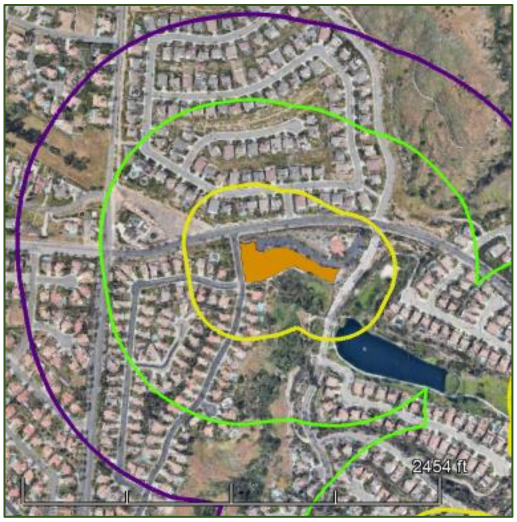

Figure 1. Example area 1 (left) and 2 (right): potential buffer zones of 100 m (yellow), 250 m (green) or 400 m (purple) around commercial groves (orange). Imagery from Google Earth Pro. 2020.

Figure 2. Example area 3: Potential buffer zones of 100 m (yellow), 250 m (green) or 400 m (purple) around commercial groves (orange). Inset shows the full expanse of the indicated buffers with the zoomed-in area outlined in white. Imagery from Google Earth Pro. 2020.

Table 1. The number of residential properties present in buffer zones of various sizes in each example area.

	Residential Properties present in buffer zone size:			
	100 m	**200 m**	**300 m**	**400 m**
Example Area 1	23	97	190	290
Example Area 2	20	44	76	82
Example Area 3	101	236	369	472

Treatment efficacy

We are aware of two projects that have directly or indirectly measured the efficacy of buffer zone treatments in Southern California. The first was conducted in 2017 and 2018 by Dr. Beth Grafton-Cardwell (UC Riverside) in Ventura and Riverside. This project found that Tempo and Merit applied together were fully effective within four weeks (data not shown). The second project is currently underway by Dr. Greg Simmons (USDA APHIS) and Dr. Richard Stouthamer (UC Riverside). This is a large demonstration project in Hemet and has shown significant reductions in ACP caught on traps per day in buffer zones compared with untreated areas (data not shown). Both of these projects justify continued use of buffer treatments around commercial groves.

ACP Flight

Work underway by Dr. Monique Rivera (UC Riverside) and Dr. Xavier Martini (University of FL) has evaluated the flight performance of ACP in relation to temperature and humidity using a custom-made flight mill. Although their work has shown that "long-distance" flyers can travel 500 m on average, this occurs under ideal temperature conditions and shorter flights were observed more frequently. The spatial clustering of HLB+ trees in Southern California also supports the predominance of shorter-distance flights, as 95% of infected trees are within 215 m of another HLB+ tree, and this number has remained under 250 m for nearly two years.

Conclusions and Implementation

The goal of buffer treatments is to limit ACP incursion from residential areas into commercial groves, so it should be optimized for that purpose. Specifically, location and timing should be optimized to minimize ACP dispersal, triggered by buffer treatments, into groves. We recommend the program be structured to accomplish this by applying treatments first to the properties nearest to groves (within the first 100 m) and moving outward upon completion. Although there is not strong evidence to support reducing the total size of the buffer zone, a reduction could tighten application windows, thereby increasing insecticide efficacy, as well as cut costs. If the program decides both these goals are priorities, we recommend the zone be reduced to 250 m from 400 m, with the timing caveat outlined above.

Seasonal variability of Ct Values in CLas-positive samples collected in Southern California: Update

Holly Deniston-Sheets[1]
Lukasz Stelinski[2]
Greg McCollum[3]
Neil McRoberts[4]

[1] Citrus Research Board
[2] Department of Entomology and Nematology, University of Florida
[3] US Horticultural Research Laboratory, Agricultural Research Service, USDA
[4] Quantitative Biology & Epidemiology Lab, Plant Pathology Department, UC Davis

SUMMARY

In the summer of 2019, DATOC published a report highlighting an absence of significant seasonal differences in the Ct values of HLB+ plant samples in California. In the most current dataset available at that time, 1,047 HLB+ trees had been detected. Now, a year later, an additional 843 diseased trees have been added to the dataset and we have completed a similar analysis to update the results. As in 2019, there remains no significant effect of season on bacterial titers, although they are otherwise increasing over time.

BACKGROUND

In other areas of the world, researchers have suggested optimal times to sample for *Candidatus* Liberibacter asiactus (*C*Las) detection based on observed seasonal variations of *C*Las titers in citrus trees. We investigated whether this was the case in California, to help guide the regulatory sampling plan.

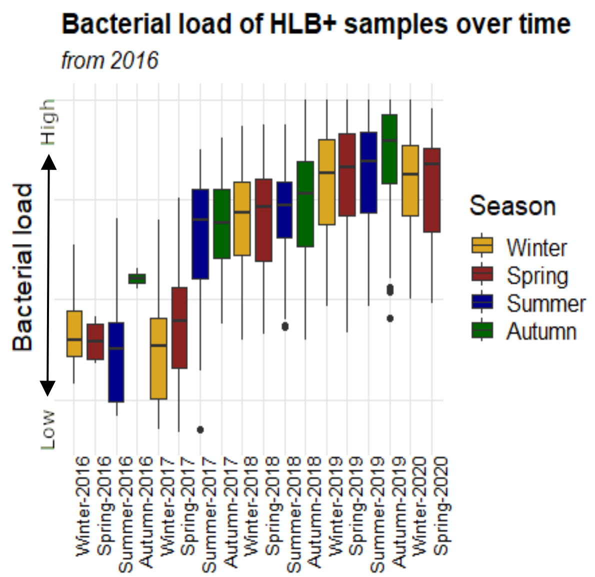

Figure 1. Log copy number distribution of *C*Las+ plant samples indicating the median (horizontal line), first and third quartiles (lower and upper hinges) and largest and smallest value less than 1.5 * the interquartile range. Points represent outliers. For samples tested with 16S primers, calculated as 11.5 – (0.33*Ct). For samples tested with RNR primers, 11.5 – (0.27 *Ct).

EVIDENCE

We examined the effects of year, season, and city on titers using ANOVA. Variety was not included, as differences were not clearly defined in the dataset. We found that year and city were significant, but season was not ($p > 0.4$). We also examined the effects of sample size to determine if fewer samples earlier in the epidemic could be confounding results, as the number of samples tested yearly has tripled since earlier years. However, we found no significant effect of sample size using stepwise model selection.

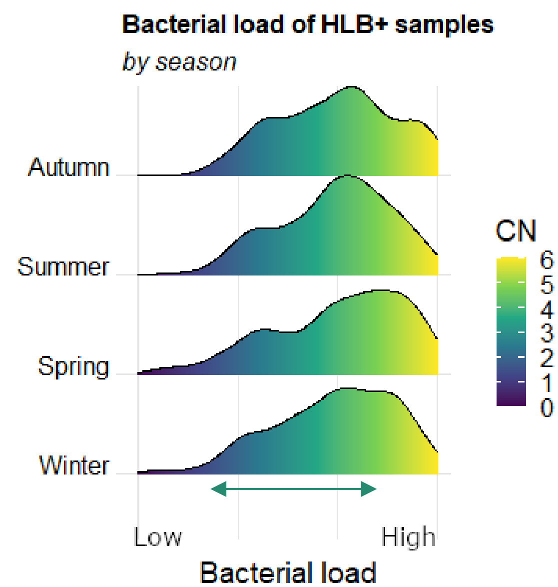

Figure 2. Log copy number density by the season in which the sample was collected.

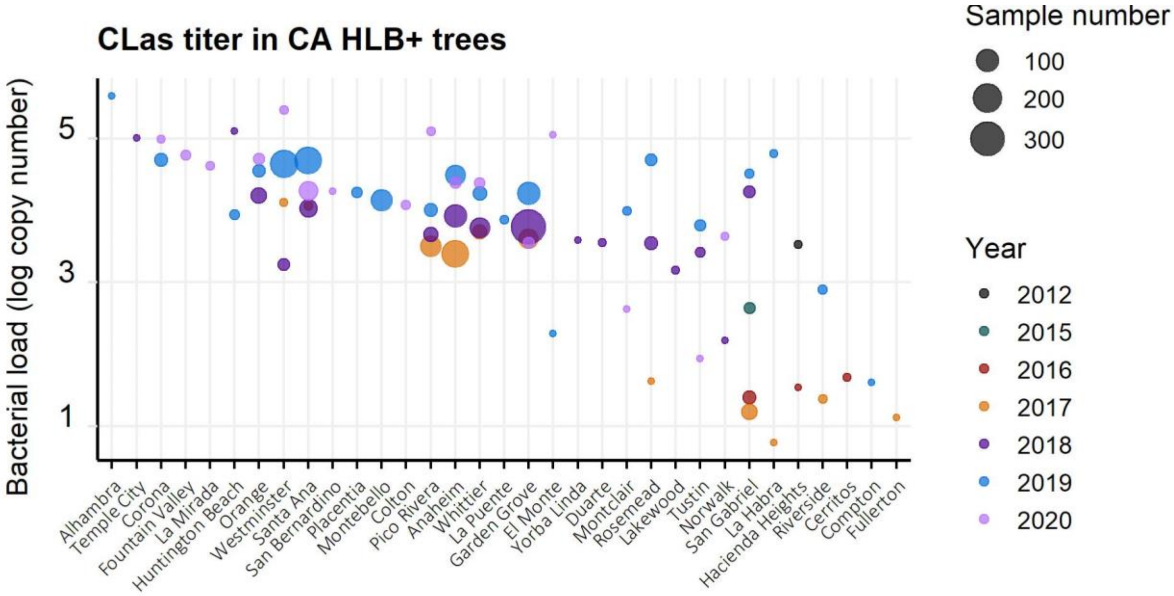

Figure *3.* Mean log copy number of HLB+ plant samples in CA cities each year. The size of the point indicates the number of samples taken per year in that city. Cities are ordered by mean log copy number (high to low).

CONCLUSIONS & CONSIDERATIONS

In summary, *C*Las-positive plant samples collected from residential areas in southern California show no significant seasonal differences in bacterial titers. This diversion from patterns observed elsewhere could be due to differential growth patterns under California climatic conditions and/or variable residential watering regimes, which could in turn affect bacteria movement within the phloem.

This conclusion should be revisited in the future if significant numbers of *C*las-positive plant samples are collected from commercial groves in California, as the differences in the growing environment between residential areas and commercial groves could affect the results of the analysis.

Summary of analyses relevant to the cost effectiveness of urban tree removal

Holly Deniston-Sheets[1]
Monique Rivera[2]
Neil McRoberts[3*]

[1] Citrus Research Board
[2] Entomology Department, UC Riverside
[3] Plant Pathology Department, UC Davis
* Listed authors contributed to report production, but all panelists were equally involved in discussions summarized herein.

Introduction

At various times, DATOC has been requested to provide input into the structure of, and potential changes to, the CPDPD HLB/ACP management program. Questions have included:

- What are the metrics to consider when making the decision to terminate residential HLB+ tree removal?
- What is the trigger point at which the program should change?
- Can we quantify the effects of the current program?

DATOC has discussed such questions extensively, and although it has been difficult to generate explicit guidance, we provide here a summation of some key points to serve as a springboard for further Subcommittee discussion.

Discussion Framework

All discussions of program activities are considered within the framework of program policies, goals, and objectives. DATOC believes the program's primary goal is to slow the spread of HLB into commercial orchards until a more permanent solution, such as a resistant rootstock, is available. A subsidiary goal is to minimize the rate at which infected ACP spread from infected trees.

Economic Considerations

The primary motivation for a potential restructure of program activities appears to be a concern that money is being spent in a cost-effective manner. There are currently no funding constraints on program activities, but there are personnel constraints. This may be mitigated somewhat following the recent transformation of the Program into a stand-alone Division.

Regarding residential tree removal, we should consider how much of the program resources are consumed by the activity. If it is performed by contractors, ceasing tree removal may not actually free up those resources which are in shortage (namely, personnel) to such extent that could make a difference in disease management by being redirected to other activities.

For the 2019 - 2020 FY, $6.5M was budgeted for HLB+ tree treatment and removal. Another $1.8M was budgeted to delimitation surveys around detections. Total projected spending for the fiscal year is $8.8M for both categories combined, representing 26% of projected expenditures (or 22% of the total budget, Fig. 1).

Based on data provided by CDFA, one property with one host costs approximately $240 to survey, test, and treat on average. This equates to, on average, approximately $13,000 (or 0.03% of the total budget), for one 250 m delimitation zone. It should be noted, though, that because 95% of HLB+ trees are found within 250 m of another diseased tree, we cannot project the yearly total cost of delimitation activities based on the number of diseased trees found in a year.

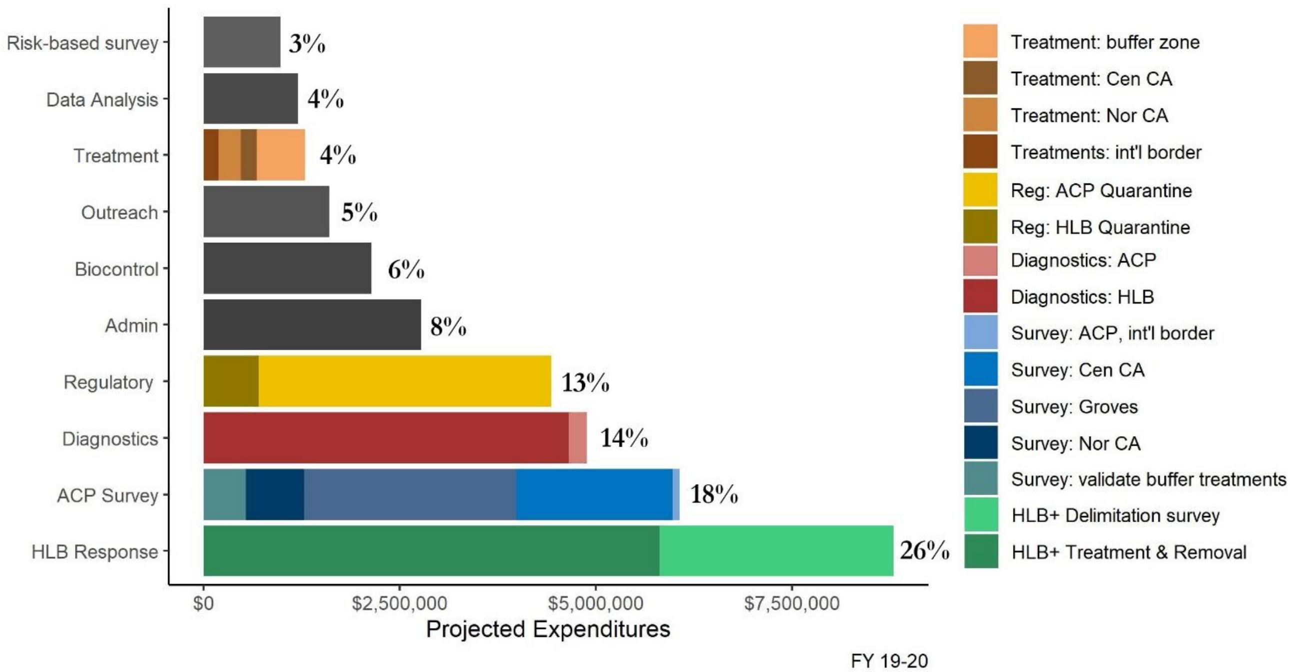

Figure 1. Projected expenditures for fiscal year 2019 - 2020, according to a report given on September 1, 2020 to a meeting of the CPDPD Finance Subcommittee. Percentage indicates the percent for that activity category out of all projected expenditures (>100% due to rounding).

There are concerns that our current strategies will be unsustainable if, in the future, there are significant numbers of HLB detections in commercial groves. In this case, CPDPD has outlined a response in the section of their Strategic Planning document called Scenario 3: Partial Infestation (of commercial groves). This document calls for an evaluation of whether to shift resources in this scenario from urban areas to commercial protection, but detection and removal of diseased trees is still listed as the top priority.

If California moved into Scenario 3 and the program did not change its current strategy, testing costs for commercial groves could quickly become a significant cost to the program. We have outlined a few example scenarios, in 5 different areas representing varying levels of commercial groves around a hypothetical HLB+ find (Fig. 2). We calculated the cost to the program to test perimeter trees in each grove within 400 m of an HLB find (calculations were performed before the shift to a 250 m delimitation radius). We used the cost of $20/sample provided to us by the Citrus Pest Detection Program (formerly the Central California Tristeza Agency; testing by the CDFA lab is slightly more expensive). The cost to sample all perimeter trees in these cases ranged from $8,800 - $28,000, with an average of $19,000.

Figure 2. Clockwise from top left, sample areas 1 - 5. The circle represents a 400 m radius from a hypothetical HLB find; areas outlined in orange are commercial citrus groves.

Residential Strategy & Disease Progression in CA

The goal of diseased tree removal is to reduce the number of infected ACP by reducing the probability that uninfected ACP acquire CLas from infected trees. Although while the high false negative rate for tree testing, due to sampling error, means infected trees may remain undetected, insecticide treatments validated by CLas detections likely do reduce *infected* ACP populations, thus it may be premature to discard any current activities without a good alternative.

The proportion of ACP with Ct values < 38 within 1 or 2 km of HLB+ trees has been increasing since 2012, but this increase has been dramatically slower in CA compared to TX (Fig 3). Other differences have also become apparent over time. The proportion of ACP tested overall that are CLas+ is drastically lower compared with populations in TX and FL. Although we do not yet have an answer for why this is the case, there could be a synergy between various control tactics (e.g. AWM, biocontrol, buffer treatments, HLB delimitation, etc.) and between those tactics and unfavorable climates in some counties (Fig. 4).

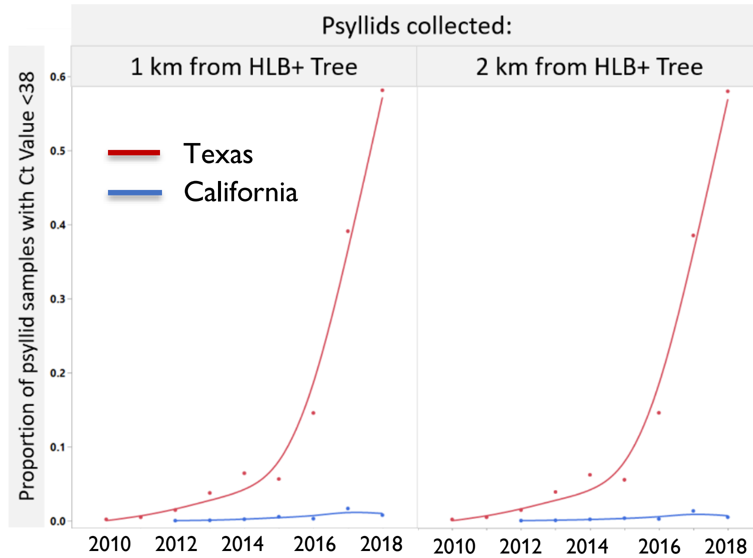

Figure 3. The proportion of ACP collected within 1 km (left) or 2 km (right) of an HLB+ tree in Texas (red) or California (blue) from 2010 – 2018. Data courtesy of Dr. David Bartels, USDA.

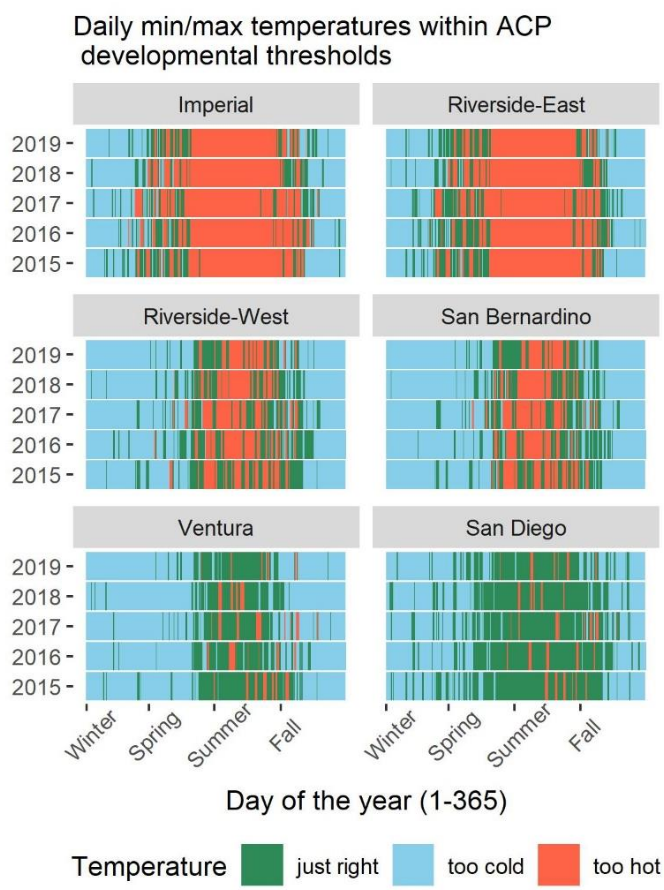

Figure 4. An indication of suitable and unsuitable days for ACP development, determined by the minimum and/or maximum temperature, in Southern CA counties.

Population Connectivity

There is evidence that California commercial groves near residential areas have higher ACP populations. Proximity to residential areas has also been determined as an ACP risk factor for Texas groves. Higher psyllid populations can be considered a reasonable proxy for risk of *C*Las transmission, so uncontrolled residential populations pose a significant risk to commercial groves. We should keep in mind that experimental longest sustained flight measurements for ACP do not indicate how far ACP can travel over time; rulemaking should consider the latter. Populations of infected psyllids from residential trees pose significant risk to groves up to several km away.

Options for Alternative Strategies

Regardless of other potential program changes, DATOC believes the timely implementation of a standardized, electronic data collection system would greatly increase our ability to evaluate the program. Survey activity can account for over 25% of program expenditures, therefore our ability to cost-effectively access and analyze <u>all the data collected</u> is critically important, especially in light of the high false-negative rate of PCR testing for host plants. Data collection tools should utilize drop-down menus or autocomplete for fields like host, city, survey type, etc., to minimize human error. The system should include the number of host trees for each surveyed property, in a method that is easily queried, as well as if samples were symptomatic or not. When more data are compiled in one place, activity and outreach can be better tailored to regional needs. Visual data on delimitation and buffer treatment results should be presented on completion to the CPDPD committees, and potentially to relevant local groups.

Defensive Borders

A "defensive border strategy" focused on commercial citrus could be explored. However, a 1-mile wide buffer around all the commercial citrus in the state would encompass a larger area than is currently covered by the risk-based survey and HLB delimitation areas combined; a 1-mile buffer would encompass 4,000 mi^2. All the STRs included in the most recent risk-based survey encompass only 1,000 mi^2, and HLB delimitation zones encompass only 25 mi^2 (measured using the newly adopted 250 m radius). If this tactic were employed just around Southern California commercial citrus, a 1-mile buffer would encompass less than 2,000 mi^2. Various sized zones, statewide, or just for Southern CA, are given in Figure 5. In this case, Southern CA includes Imperial, Los Angeles, Orange, San Bernardino, San Diego, Riverside, and Ventura counties (Fig. 6, next page).

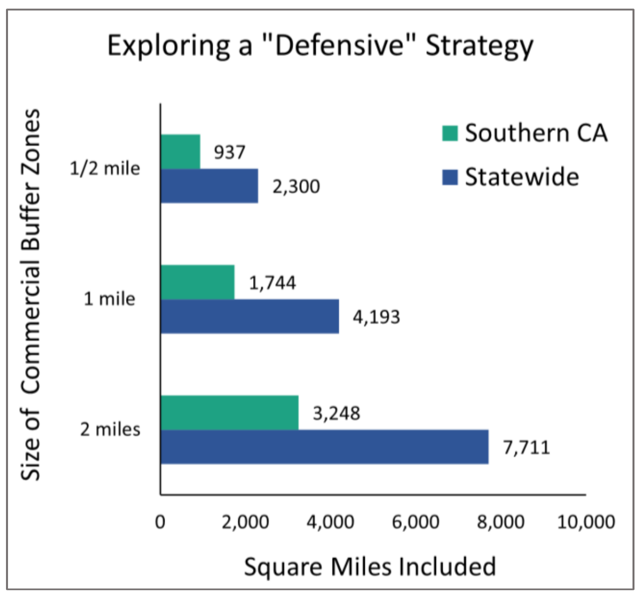

Figure 5. The square miles contained within possible buffer zones of various widths around commercial citrus, either in Southern CA only or statewide.

A "containment" border around the HLB quarantine zone has also been suggested (Fig. 7). In this case, a 1-mile buffer would contain 290 mi^2; a 2-mile buffer would contain 550 mi^2. In this zone, there are 1,060 acres of commercial citrus. If buffers around this acreage were also initiated, they would cover either 160 mi^2 (1-mile buffer) or 400 mi^2 (2-mile buffer).

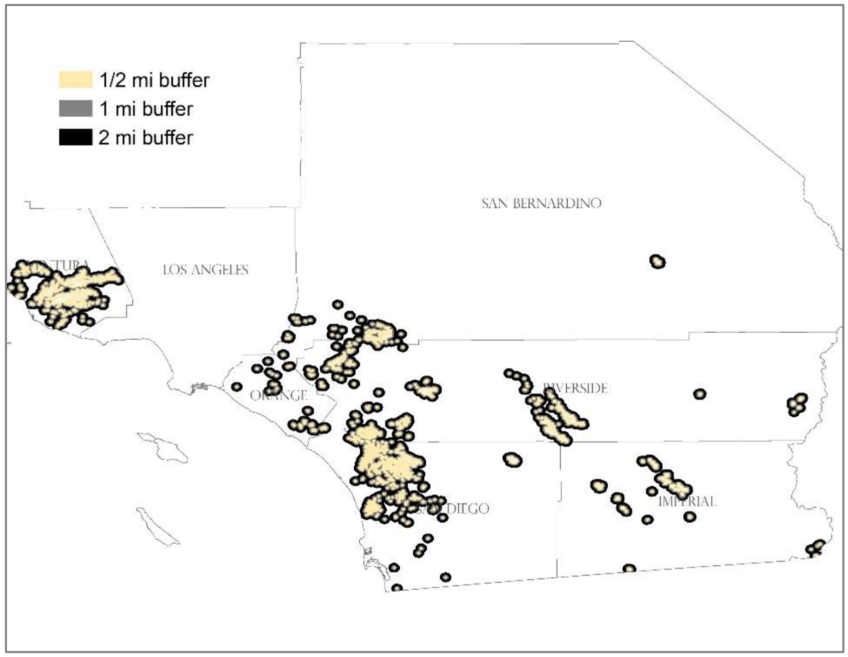

Figure 6. A visual depiction of potential buffer zones around commercial citrus in Southern CA (right).

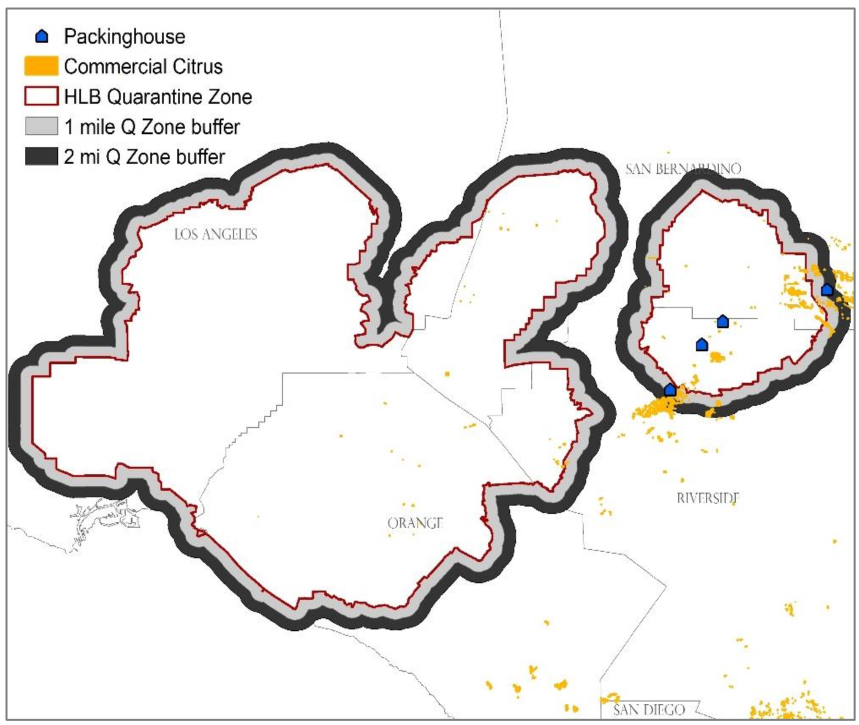

Figure 7. Possible "containment" buffer zones around the current HLB quarantine zone (red).

Regional & Situational

A regional strategy would switch the primary focus from HLB eradication to ACP management and control, and restructure budget and program activities to target specific areas to leverage periods of low climatic suitability, thereby pushing populations as low as possible. These activities would include the continued use of imidacloprid and beta-cyfluthrin, the rotational use of other materials, if possible, and in areas where initial ACP populations are high, application of a third insecticide at a later date. The latter two suggestions will require amendments to the Program Environmental Impact Report.

For areas that have consistently high suitability (e.g. San Diego), enact stringent regulations to discourage non-compliance with ACP-control measures and to encourage hobbyists and low-input farmers to exit citrus altogether. For areas which typically see high grower coordination, resources could be allocated to incentivize grower treatments, provide an inundative and innovative biocontrol program (including a diversified set of predators and/or parasitoids), and demonstrate fence barriers and trap plants dosed with systemics as protective systems.

Canine Reconnaissance

In areas without established ACP populations, such as the Central Valley, ACP-detector dogs can be used to scout for psyllids to trigger regulatory insecticide applications and to guide local groups coordinating non-regulatory actions (Figure 8).

Similarly, HLB-detector dogs can be used to scout and map trees in Southern California to support a "tree removal and replacement" public-outreach program that gives residential citrus tree owners the option to either spray their trees, "exchange" them for an alternative fruit tree, or replace them when a resistant variety is available. When the incidence of dog alerts reaches a predetermined threshold, implement bio-control measures and wide-scale tree removals based on the "exposure" abatement in the ag code.

Plan ways to redirect the Outreach budget to actively sell the new program.

Figure 8. An exuberant ACP detection scout. Courtesy Lisa Finke, Canine Detection Services.

A More Robust Tree Removal and Replacement Program

Some on DATOC have suggested exploring the development and implementation of a more robust, incentive-based residential tree removal and replacement program than what has been available through CCM. Such a program could remove only those trees which pose the biggest risks to commercial citrus, which are usually located within 2 km of a grove. This exercise would require looking at (1) whether current 281 legislation could be used, or amended, to allow either CDFA or another quasi-public organization to use a portion of the current 281 assessment for incentives, and (2) other modes for funding incentives, such as annual contributions from large retail grocery chains, agriculture chemical companies, or other citrus industry participants. It is believed that many residential tree-owners, if given the options to either (1) voluntarily remove their ostensibly healthy tree today for "reasonably attractive" compensation, or (2) likely be administratively required to remove their tree at some time in the future for zero compensation, will choose the former.

Concluding remarks

There is a body of research available which details strategies that are consistently found in successful collective action programs[1]. As the program evolves, we suggest that these strategies be considered, and incorporated into the program where possible. As it stands, many principles have already been included, such as utilizing people who are well respected in their communities to bridge the gap between the local and state level (i.e. Grower Liaisons), having an elected committee which votes on self-imposed regulations for the industry, and matching regulations to local conditions. The program has also been intentionally adaptable; the Committee has examined updated data as circumstances have changed, questioned previous decisions, and enacted new policies that are better suited to the new circumstances. We suggest the Committee continue in these strategies, strengthen them where possible, and adopt others. For example, a system developed by the community to monitor the behavior of others could be implemented. This could take the form of an online forum where PCAs could discuss ACP populations in their area, or any other variety of systems. These efforts will help to continue building and maintaining community trust, which is a vital aspect of the program's sustainability.

[1] *Information courtesy of Sara García Figuera, UC Davis.*

Perceived vulnerability and propensity to adopt best management practices for huanglongbing disease of citrus in California

Sara Garcia-Figuera[1], Holly Deniston-Sheets[2], Elizabeth Grafton-Cardwell[3], Bruce Babcock[4], Mark Lubell[5], and Neil McRoberts[1]

[1] Department of Plant Pathology, University of California – Davis, One Shields Ave, Davis, CA 95616, U. S. A.

[2] Data Analysis and Tactical Operations Center, Citrus Research Board, 217 N Encina St, Visalia, CA 93291, U. S. A.

[3] Department of Entomology, University of California – Riverside, Citrus Dr, Riverside, CA 92521, U. S. A.

[4] School of Public Policy, University of California - Riverside, 900 University Ave, Riverside, CA 92507, U. S. A.

[5] Department of Environmental Science and Policy, University of California – Davis, One Shields Ave, Davis, CA 95616, U. S. A.

*Corresponding author: Sara Garcia-Figuera. Email address: sgarciafiguera@ucdavis.edu

ABSTRACT

Huanglongbing (HLB) disease of citrus, associated with the bacterium "*Candidatus* Liberibacter asiaticus", is confined to residential properties in Southern California eight years after it was first detected in the state. To prevent the spread of HLB to commercial citrus groves, growers have been asked to adopt a portfolio of voluntary best management practices. This study evaluates the citrus industry's propensity to adopt these practices using surveys and a novel multivariate ordinal regression model. We estimate the impact on adoption of perceived vulnerability to HLB, intentions to stay informed and communicate about the disease and various socio-economic factors, and reveal what practices are most likely to be jointly adopted as an integrated approach to HLB. Survey participants were in favor of scouting and surveying for HLB symptoms, but they were reluctant to test trees, use early detection technologies (EDTs) or install barriers around citrus groves. Most practices were perceived as complementary, particularly visual inspections and some combinations of preventive practices with tests and EDTs. Participants who felt more vulnerable to HLB had a higher propensity to adopt several practices, as well as those who intended to stay informed and communicate with the coordinators of the HLB control program, although this effect was modulated by the perceived vulnerability to HLB. Communication with neighbors and the size of citrus operations also influenced practice adoption. Based on these results, we provide recommendations for outreach about HLB management in California and suggest future directions for research about the adoption of plant disease management practices.

Keywords: huanglongbing, biosecurity, adoption, best management practices, integrated pest management, risk perception

INTRODUCTION

Since HLB was first detected in the state of California in 2012 (Kumagai et al., 2013), the citrus industry has taken a proactive role in dealing with this devastating disease. In response to lobbying by and discussion with citrus industry leadership, the state Legislature passed a bill in 2009 requiring the Secretary of Agriculture to establish the California Citrus Pest and Disease Prevention Committee (CPDPC). The CPDPC is composed of citrus industry representatives who make recommendations to the California Department of Food and Agriculture (CDFA), which then implements activities under its regulatory jurisdiction (De Leon, 2009). Activities enforced by CDFA, which include detection and removal of HLB-positive trees, are primarily funded by grower assessments on each carton of fruit harvested, but because funds are limited, voluntary activities by commercial growers are also encouraged. A task force of grower representatives and researchers was appointed to collaboratively develop a *Voluntary Grower Response Plan for Huanglongbing*, which contains the best management practices recommended by the CPDPC to control the spread of HLB (CPDPP, 2019). The voluntary plan was presented to the California citrus industry for the first time in 2019 at a series of industry seminars. We took the opportunity offered by those seminars to assess how likely it was that those practices would be adopted, evaluate what practices within the portfolio might be adopted together, understand what factors might influence adoption, and identify potential targets for outreach.

The adoption of best management practices by growers has been the subject of many studies and recent reviews (Liu et al., 2018; Prokopy et al., 2019). A common approach is to organize surveys, participatory workshops, or interviews to assess the growers' willingness to adopt best management practices while gathering information about their personal and farm operation characteristics, or other contextual factors that could help predict adoption (Prokopy et al., 2019; Puente et al., 2011). The adoption of agricultural practices in general has been found to be influenced by growers' attitudes towards the practices, financial motivations, problem awareness, information seeking behavior, previous adoption of related practices, farm size and income (Prokopy et al., 2019). For Integrated Pest Management (IPM) in particular, early studies determined that IPM adoption by vegetable growers in the US was influenced by farm size (Fernandez-Cornejo et al., 1994), while IPM adoption by coffee growers in Colombia was influenced by education and wealth (Chaves and Riley, 2001). Over the years, other contextual factors have been found to impact IPM adoption, such as farm location and pest intensity (Kaine and Bewsell, 2008), social networks and trusted sources of information (Hillis et al., 2016; Sherman and Gent, 2014), and cost efficacy of the practices (Hillis et al., 2017).

Fewer studies have examined the socio-economic and contextual factors that influence the adoption of management practices for invasive pests and diseases, which require quick decision making to prevent spread, but are associated with high uncertainty about risk and lack of previous experience (Simberloff et al., 2013). Neither of the two components of risk –likelihood of spread and establishment and potential negative impact – are commonly known at the time management decisions about invasive pests or diseases need to be made, which may lead to perceptions of risk to be subjectively constructed (McRoberts et al., 2011).

In the human disease literature, early behavioral models proposed that risk perception, comprising *perceived vulnerability* (how susceptible an individual felt to a communicated threat, related to likelihood) and *perceived severity* (how serious the individual believed the threat would be, related to impact), was a key factor the decision to adopt self-protective behavior (Sheeran et al., 2017). One of the most widely accepted models, the Protection Motivation Theory, proposed that the more vulnerable individuals perceived themselves to be to a threat and the more serious they believed it to be, the more likely they would be motivated to protect themselves (Rogers, 1975; Rogers, 1985). Assuming that a similar cognitive process drove the intention to adopt protective behavior against plant and animal diseases, risk perception was also considered a key factor in predicting adoption of management practices for these threats (Heong and Escalada, 1999; Ritter et al., 2017).

However, the limited evidence available provides inconsistent support for a positive relationship between risk perception and adoption of management practices for invasive plant diseases. A Netherlands study showed that the adoption of management practices for several invasive diseases varied by crop, and that risk perception was negatively correlated with adoption (Breukers *et al.*, 2012). The authors' interpretation was that growers who said they had suffered past invasions and adopted management practices probably felt more protected, and thus perceived a lower risk of future invasions (Breukers et al., 2012). This negative feedback loop between protective behavior and risk perception had already been observed in studies of human diseases (Weinstein and Nicolich, 1993). For example, people who received the Lyme disease vaccine showed a greater decline in their perceived risk of getting the disease than people who had not been vaccinated (Brewer et al., 2004).

As a result, three different hypotheses emerged in the human disease literature to describe the relationship between risk perception and self-protective behavior. The *behavior motivation hypothesis*, heir to the Protection Motivation Theory, proposed that people's risk perception had a causal effect on their health behavior, so that a higher risk perception at one point in time would lead to increased health behavior in the future, evidenced by a positive correlation between both factors in a longitudinal or experimental study (Brewer et al., 2004). The *risk reappraisal hypothesis* proposed that if an action was believed to reduce risk, people who took the action would subsequently lower their risk perception in the future, explaining the negative correlations found in the Netherlands study (Breukers et al., 2012) and the Lyme disease study (Brewer et al., 2004). Finally, the *accuracy hypothesis* proposed that people who engaged in risky behavior at a given point in time had higher actual risk and would perceive a higher level of risk, evidenced by a negative correlation between protective behavior and risk perception at that point in time (Brewer et al., 2004).

These three complementary hypotheses, that emerged to explain positive or negative correlations between risk perception and protective behavior against human diseases, highlight the importance of the time point when studies are conducted for interpreting results (Gaube et al., 2019), something which has rarely been considered in the context of plant diseases. A recent study conducted with banana growers during the first few months after an outbreak of the invasive Panama tropical race 4 (TR4) disease in Australia showed that growers perceived a high level of risk, but it was not significantly correlated with proactive action against the disease (Mankad et al., 2019). The authors' interpretation was that fear of Panama TR4 was not the main motivation to engage in control, and other factors such as income dependency on bananas and perceived self-efficacy could be stronger predictors of propensity to act. Considering the Protection Motivation Theory and the adoption literature, these authors called for further studies to understand drivers of engagement in control against invasive plant diseases (Mankad et al., 2019).

This article uses HLB as a case study to examine the relationship between perceived vulnerability and grower adoption of management practices against invasive plant diseases at a unique point in time. HLB is an invasive bacterial disease that poses a major threat to citrus production worldwide (Wang, 2019). Most commercial citrus cultivars are susceptible to HLB, and infected trees suffer a rapid decline characterized by blotchy mottle symptoms on foliage, premature fruit drop and poor fruit quality, which lead to considerable economic losses before the eventual death of the tree (McCollum and Baldwin, 2016). The most prevalent type of HLB is associated with the bacterium "*Candidatus* Liberibacter asiaticus" (*C*Las), which is transmitted by grafting or by an insect vector, the Asian Citrus Psyllid (ACP), *Diaphorina citri* (Grafton-Cardwell et al., 2013). HLB has spread from Asia to the main citrus-producing regions in North and South America, where it has had a devastating impact in Brazil (Bassanezi et al., 2020), Florida (Graham et al., 2020), Mexico (Robles González et al., 2018), and Texas (Sétamou et al., 2019).

HLB was first detected in California in 2012. Since then more than 2000 HLB-positive trees have been detected and removed from residential properties in Los Angeles, Orange, Riverside and San Bernardino counties (CPDPP, 2020b). Commercial citrus production is distributed between the Coastal and Southern counties, where the ACP is widespread, and the Central Valley, where there have been a few isolated ACP detections that have been quickly eradicated (Grafton-Cardwell, 2020). Although HLB-positive trees have not been detected in any commercial citrus groves yet, a *C*Las-positive ACP was recently detected in a commercial grove in Riverside (CPDPP, 2020a), and there is fear that positive tree detections will soon follow.

We contribute to the emerging interdisciplinary literature on the adoption of management practices for invasive plant diseases by assessing the California citrus industry's propensity to adopt a portfolio of voluntary management practices to prevent the spread of HLB. Through a survey distributed to 300 participants in three different grower meetings, we analyze adoption in a perennial cropping system, after introduction of an invasive disease that cannot be eradicated, but before it has had an impact on commercial production. At this unique point in time, characterized by high risk and high uncertainty, we assess the citrus industry's perceived vulnerability to HLB, validate its accuracy based on geographical proximity to HLB detections, and show how it has changed over the course of the HLB epidemic in California, thus providing an update to a previous study (Milne et al., 2018). More importantly, we show how a multivariate ordinal regression model can be used to simultaneously evaluate the propensity to adopt a portfolio of management practices rated on an ordinal scale, assess the relationship between perceived vulnerability, information, communication and propensity to adopt, and reveal which practices are more likely to be adopted together. Given the developing HLB situation in California, information to support strategic planning of the response is urgently needed. Based on the study's results, we provide recommendations for outreach about HLB management in California and suggest future directions for research about the adoption of plant disease management practices more generally.

MATERIALS AND METHODS

The Voluntary Grower Response Plan

The CPDPC appointed a task force of grower representatives and University of California (UC) researchers to put together a set of voluntary best management practices that would be provided to the growers as a toolbox from which to choose practices to prevent the spread of HLB. Four hypothetical scenarios were defined by proximity to confirmed HLB detections to facilitate grower visualization of possible contexts for adoption, and specific protocols to implement the practices varied depending on the scenario. The *Voluntary Grower Response Plan for Huanglongbing in California* was officially published in May of 2019 (CPDPP, 2019); it was presented to the citrus community by the third author immediately before the survey that is the subject of this study.

The task force decided to leave early detection technologies (EDTs), which comprise any technology that can detect *C*Las before the regulatory quantitative polymerase chain reaction (qPCR), out of the portfolio of recommended practices because none of the EDTs was commercially available at the time the plan was published. However, we decided to include EDTs in this study because at least one of them was imminently going to be available and evaluated (Gottwald et al., 2020), and at least that one was probably going to be considered by the citrus industry. For the same reason, we decided to also assess the propensity to use bactericides approved for *C*Las control, which have been tested against HLB and used in Florida (Al-Rimawi et al., 2019; Hu et al., 2017), even though they were not included in the *Voluntary Grower Response Plan*.

Theoretical framework

The propensity to adopt the recommended management practices for HLB in California was studied as a function of a set of predictor variables selected from the Protection Motivation Theory, the technology adoption-diffusion literature and similar studies in plant disease management.

The HLB management practices recommended by the *Voluntary Grower Response Plan,* with the addition of EDTs and bactericides, are the dependent variables in our regression model. To frame our analysis in the context of the IPM literature, eight selected practices were simplified and grouped into three categories: monitoring, prevention and suppression. Monitoring and the proper identification of pests and diseases are considered the basis for IPM decisions (Farrar et al., 2016), and this category includes scouting for ACP nymphs on flush; conducting visual surveys for HLB symptoms; voluntarily sending citrus leaves and ACP to be tested by an approved laboratory using a direct method of detection such as qPCR; and using EDTs. Prevention is defined as the practice of keeping a pest or disease from infesting a field or site (Farrar et al., 2016), and this category includes adopting extra measures such as bags or repellents to protect new citrus plantings; using physical barriers such as mesh or windbreaks around the groves; and applying extra pesticides and repellents to the grove perimeters. Suppression is defined as the control of infestations or epidemics to prevent pest or disease levels from becoming economically damaging (Farrar et al., 2016), and this category only includes the use of bactericides.

To align this study with the adoption literature, staying informed and communicating with the grower liaisons and communicating with neighbors, which were recommended in the *Voluntary Grower Response Plan*, were selected as explanatory factors related to actively seeking information and interacting with social networks, both of which have been found to be important determinants of the adoption of agricultural practices (Prokopy et al., 2019). The HLB control program in California has established a formal information network in which *grower liaisons,* individuals with local connections and experience as managers or advisors for the citrus industry, were hired as coordinators and knowledge brokers between the state-wide program and the citrus growers at the county or regional level. Therefore, we specifically chose to identify them as the main source of information about HLB. At the same time, informal networks have been repeatedly identified as relevant sources of information about agricultural practices (Hoffman et al., 2015), so we included a question about communication between neighbors to test if informal information networks could be a relevant factor in the adoption of HLB management practices in California, as has been the case for other plant diseases (Maclean et al., 2019; Sherman et al., 2019).

A core hypothesis and four complementary hypotheses shaped the design of this study. According to the Protection Motivation Theory, **we expected the perceived vulnerability to HLB to have a positive impact on the propensity to adopt the recommended practices (H1)**. We chose to focus on the likelihood component of risk (i.e., perceived vulnerability) because we assumed that the citrus industry in California would be familiar with the high impact associated with HLB epidemics, considering the widespread knowledge of the devastating consequences of HLB in Florida (Kuchment, 2013). Compared with previous studies that measured the impact of risk perception on invasive plant disease management (Breukers et al., 2012; Mankad et al., 2019), this study was conducted at a time when participants already knew about the potential impact of an HLB epidemic in California, but they did not have any experience implementing the recommended practices in commercial groves, so we did not expect the *accuracy hypothesis* and the *risk reappraisal hypothesis* to be relevant to this case (Gaube et al., 2019). Therefore, we did not expect a negative relationship between perceived vulnerability and practice adoption.

We first aimed to evaluate whether the perceived vulnerability to HLB was accurate, and we compared it with a previous assessment done four years ago (Milne et al., 2018). Then, we expected the participants' perceived vulnerability to HLB to have a positive regression coefficient on the eight practices considered in the multivariate ordinal regression model, since they would all improve the level of protection against HLB. In particular, we expected perceived vulnerability to have a positive impact on adoption of monitoring practices because people who feel more vulnerable to HLB might have greater need to know the status of the disease on their fields.

In line with previous adoption studies, **we expected the propensity to stay informed and communicate with grower liaisons to have a positive impact on the propensity to adopt the recommended practices (H2)**. Again, a positive relationship could be expected for all the practices considered, but we expected it to be particularly noticeable for some of the monitoring practices, as the HLB control program and the grower liaisons have been promoting these practices since the beginning of the HLB epidemic in California. In fact, this hypothesis allowed us to examine the level of acceptance and potential effectiveness of the grower liaisons as sources of information and promoters of the HLB control program.

Because HLB is an invasive disease that can rapidly spread across a landscape and requires coordination beyond property boundaries for effective control (Bassanezi et al., 2013; Graham et al., 2020), **we expected communication with neighbors to have an impact on the propensity to adopt some of the recommended practices**

for HLB (H3), and we were interested in determining the sign of the coefficient for this impact for different practices. Communication between neighbors might facilitate sharing positive experiences and ultimately foster the adoption of beneficial practices (Sherman et al., 2019), but at the same time, lack of intention to communicate with neighbors might indicate distrust and motivate the adoption of practices to provide protection against inoculum coming from neighbors (Maclean et al., 2019). We were also interested in identifying what practices were positively impacted by communication with neighbors, as they might be more likely to be adopted in a coordinated manner. Previous studies have shown that face-to-face communication is essential to develop trust and reciprocity to coordinate efforts in plant disease management (Sherman et al., 2019), and growers who were active participants in their community were more willing to cooperate to control pests than those who were not active members (Stallman and James, 2015).

Individual socio-economic factors were expected to modulate the propensity to adopt some of the recommended practices (H4). Land tenure has been identified as a determinant of the adoption of many agricultural practices (Prokopy et al., 2019), so we expected grove owners to have a different propensity to adopt some practices than other citrus stakeholders. In particular, grove owners might be less willing to make an investment to adopt practices that are more expensive, such as installing barriers along the grove perimeter, which would require the removal of productive trees to make space for the barriers. Also, if voluntary tests lead to the identification of an HLB-positive tree which would trigger a quarantine, it might have significant economic consequences for the owner, so we hypothesized that grove owners might be less willing to test. Farm size has been consistently associated with increasing levels of adoption for many agricultural practices, because larger farms have more financial capital and may have lower adoption thresholds in relation with cost and time to return on investment (Prokopy et al., 2019). Thus, we expected farm size to have a significant and positive impact on the propensity to adopt the recommended practices for HLB. In line with previous studies (Prokopy et al., 2019), we expected that age would have a negative impact on adoption, as older growers might consider shorter time horizons and be less willing to make investments to protect themselves against HLB. The general feeling among the citrus industry in California is that conventional and organic growers differ in their approach to control citrus pests and diseases, so we were interested in testing if this factor had a significant impact on the adoption of HLB management practices. Finally, we expected that participants who obtained a higher percentage of their income from citrus would have a higher propensity to adopt practices to manage HLB, in line with previous studies (Mankad et al., 2019; Stallman and James, 2015).

Because the *Voluntary Grower Response Plan* was conceived as a toolkit for HLB management, **we expected the adoption of the HLB management practices to be interdependent (H5)**, which would be indicated by significant correlations between the adoption equations for different practices in a multivariate ordinal logistic regression model. Our expectation was that some of the practices belonging to the same IPM category would have a higher propensity to be adopted together, which would be indicated by significant positive correlations for the equations within each group. For example, within the category of monitoring practices, we expected people who were likely to scout for ACP nymphs on flush to also be likely to conduct visual surveys for HLB symptoms, since both practices could be implemented simultaneously, and they provide complementary information about the vector and the disease. As EDTs are a new technology for citrus growers, we were interested in determining if they were being perceived as complementary to other monitoring practices such as surveying for symptoms or testing. For preventive practices, it was unclear *a priori* if installing physical barriers along the grove perimeter would be perceived as complementary or a substitute for applying pesticides and repellents to the perimeter or taking extra measures to protect new plantings.

Survey design

The survey to assess the citrus stakeholders' propensity to adopt HLB management practices was designed by the authors and consisted of twenty questions (Supplementary text 1). The first six questions referred to the participants' social and economic background, and were based on available data (USDA-NASS, 2018), or previous similar studies (Mankad et al., 2019; Milne et al., 2018; Singerman et al., 2017; Stallman and James, 2017). For these questions, participants were asked to select from a list the categorical responses that most closely represented their situation. First, they were asked to indicate their role in citrus production, choosing between *grove owner, ranch manager, Pest Control Adviser (PCA)*, who is a professional consultant licensed by the State of California to provide pest management recommendations, *Pest Control Operator (PCO)*, who is a person or company licensed to apply agricultural pesticides to crops, and *other*. Second, participants were asked to indicate how many acres of citrus they grew or managed (farm size), choosing between *less than 5 acres*, *5-25 acres*, *26-100 acres*, *101 to 500 acres* and *more than 500 acres*. Third, they were asked what age group they were in: *less than 35 years*, *35-50 years*, *51-65 years* and *more than 65 years.* Fourth, they were asked to indicate any California counties in which they had or managed groves, choosing between Fresno, Imperial, Kern, Madera, Riverside, San Bernardino, San Diego, Santa Barbara, Tulare and Ventura. Fifth, they were asked to indicate whether they grew citrus *conventionally*, *organically* or *both* (management system). Finally, they were asked to indicate what percentage of their income came from citrus: *0-25%*, *26-50%*, *51-75%* and *76-100%*.

To assess their perceived vulnerability to HLB, participants were asked "How likely do you think it is that an HLB-positive tree will be detected in your grove in the next year (July 2019-June 2020)?". This question was in line with those asked in human disease studies (Brewer et al., 2004), and it was based on a similar question asked in 2015 (Milne et al., 2018), in order to provide an update to the citrus stakeholders' perceived vulnerability to HLB four years into the epidemic. The rest of the questions assessed the participants' propensity to adopt the best management practices recommended by the CPDPC. The wording of the practices was simplified for the survey, as indicated in the previous section, and propensity to adopt was assessed as "How likely is it that you will…?". Ordinal responses were provided on a 5-point scale of *very unlikely, unlikely, maybe, likely* and *very likely*. In two of the questions (8 and 17), a sixth option (*Don't know who the liaison is* and *Don't have enough information*, respectively) was added to identify participants who thought they lacked enough information to make a choice.

The research protocol was submitted to the Institutional Review Board (IRB) at UC Davis and it was granted "Exempt" status because it entailed low risk to participants.

Survey distribution

The survey was distributed at three grower meetings that were part of the Citrus Growers Educational Seminar Series, organized by the Citrus Research Board (CRB) in conjunction with the University of California Cooperative Extension (UCCE) in June of 2019 in Palm Desert (southeast California), Santa Paula (coastal California) and Exeter (Central Valley). These are annual seminars organized by the CRB/UCCE, for which attendees get Continuing Education units & Certified Crop Adviser hours. The availability of these credits tends to result in a larger than usual attendance for grower workshops, reducing selection bias toward only those with particular interest in a given topic. Selection bias was further limited by the fact that the annual election of citrus industry representatives for the CRB was scheduled on the day of the seminars in Palm Desert and Exeter. The three meetings had the same format. The survey was distributed directly after a presentation of the *Voluntary Grower Response Plan for Huanglongbing*. At the time the meetings were held during a single week in June of 2019, 1,484 trees had been confirmed to be infected with HLB in California since the first detection in 2012, all of them in residential properties: 7 in Riverside County, 387 in Los Angeles County and 1,090 in Orange County (CPDPP, 2020b).

The survey was introduced to the participants as voluntary and anonymous, in compliance with IRB regulations. It was presented using the TurningPoint add-in for Microsoft PowerPoint (Microsoft, Redmond, WA, U. S. A.), and responses were collected using clicker handsets from TurningPoint (Turning Technologies, Youngstown, OH, U. S. A.) that had been given to each participant before the seminar started. Participants were given about one minute to answer each question. Once the polling time was closed for each question, a summary of the responses (percentage of participants that had chosen each response) was shown to the audience and briefly discussed before moving to the next question.

In total, we collected responses from 300 participants. The average number of responses for any question in the survey was 225 (an average response rate of 75% per question). In Palm Desert, there were 95 registered attendees to the meeting and responses were collected from 59 participants. In Santa Paula, there were 131 registered attendees and responses were collected from 91 participants. In Exeter, there were 219 registered attendees and responses were collected from 150 participants. Across the three meeting locations, 160 people answered a sufficient number of questions (perceived vulnerability, communication, relevant socio-economic factors and at least one practice) to be considered for statistical analysis.

Descriptive statistics of the survey respondents

The respondent sample provided reasonable coverage of the citrus industry in California (Table 1). Among the 160 people who answered a sufficient number of questions in the survey to be considered for analysis, 44% were grove owners, 18% were ranch managers, 16% were PCAs and 2% were PCOs. The rest (20%) self-identified as *other*, which could include packers, haulers, regulators or university employees. Compared with the size distribution of orchards in the counties represented in the survey, small operations (less than 5 acres) were under-represented, comprising 15% of the sample compared with 34% of orchards in those counties, and big operations (more than 500 acres) were over-represented, comprising 38% of the sample compared with 18% of orchards in those counties (USDA-NASS, 2019). Most participants (54%) were between 35 and 65 years old, which is the most common

(56%) age range for growers in California (USDA-NASS, 2019). Participants younger than 35 were over-represented in the survey (17% vs. 6%) and participants older than 65 were slightly under-represented (29% vs. 38%) (USDA-NASS, 2019). The majority of participants (71%) grew citrus conventionally, a few (4%) organically, and some (25%) both conventionally and organically. This is representative of citrus production in California, as it is estimated that around 8% of citrus operations and 3% of acreage in the state are certified organic (USDA-NASS, 2017; USDA-NASS, 2019).

About one third (38%) of participants indicated that less than 25% of their income came from citrus, while about another third (35%) indicated that more than 75% of their income came from citrus. Participants had groves in the top 10 citrus-producing counties in California (from higher to lower acreage): Tulare (130,341 acres), Kern (66,720 acres), Fresno (56,326 acres), Ventura (18,447 acres), Riverside (17,333 acres), San Diego (11,701 acres), Imperial (10,328 acres), Madera (2,800 acres), San Bernardino (2,435 acres) and Santa Barbara (1,291 acres) (Fresno CAC, 2019; Imperial CAC, 2019; Kern CAC, 2019; Madera CAC, 2019; Riverside CAC, 2019; San Bernardino CAC, 2019; San Diego CAC, 2019; Santa Barbara CAC, 2019; Tulare CAC, 2019; Ventura CAC, 2019). Because participants were asked to indicate any counties in which they had groves (multiple response option), counties were grouped in three regions to simplify some of the analyses: *Coast* (38%), which included Ventura, Santa Barbara, combinations of Ventura and Santa Barbara, and Ventura and Tulare; Southern California or *SoCal* (22%), which included Imperial, Imperial and Riverside, Imperial and San Diego, Riverside, Riverside and Kern, Riverside and San Diego, Riverside and Ventura, San Bernardino, San Bernardino and Fresno, San Bernardino and San Diego, San Bernardino and Ventura, and San Diego and Santa Barbara; and the Central Valley or *Valley* (40%), which included Fresno, Fresno and Kern, Fresno and Madera, Fresno and Tulare, Kern, Kern and Tulare, Madera, Madera and Tulare, and Tulare.

Statistical analysis

All statistical analyses were done in the R programming environment version 3.5.3 (R Foundation for Statistical Computing, 2019) with a Windows 10 Pro version 1909, 64-bit operating system (Microsoft, Redmond, WA, U. S. A.). Differences in the distribution of responses to a question based on the groups defined by responses to another question were tested using the Kruskal-Wallis test. Pairwise comparisons of the distribution of responses between two groups were tested using the non-parametric Wilcoxon-Mann-Whitney test. Plots were created using the R package “ggplot2” (Wickham, 2016) with the complementary packages “likert” (Bryer and Speerschneider, 2016), “lemon” (McKinnon Edwards et al., 2020) and “ggraph” (Pedersen, 2020).

Grove owners, ranch managers, PCAs, PCOs and other participants did not have significantly different distributions of responses to most questions, so all categories were considered for analysis and may be referred to as “participants”, “respondents” or “growers”. In terms of correlations between socio-economic factors, farm size was positively correlated with the percentage of income coming from citrus (ρ= 0.56, P= 2.84×10^{-14}) and older participants tended to manage smaller groves (ρ= -0.27, P= 7.04×10^{-4}), but these two pairs of factors were not included at the same time in the selected model, so these correlations did not interfere with the interpretation of our results.

Relating perceived vulnerability to HLB with an objective assessment of the likelihood of HLB detection

To assess whether the participants' perceived vulnerability to HLB (*i.e.*, likelihood of HLB detection in their grove in the next year) was accurate, we compared it with an objective measure of the likelihood of HLB detection based on their geographical location. The location of the citrus groves in each county was taken from the commercial GIS citrus layer developed by the CRB (R. Dunn, *personal communication*). In the absence of individual-level coordinates for each participants' groves, the centroid of the citrus production area in the county where participants said they had groves was used as the point of origin, and we calculated the linear distance from each centroid to the closest confirmed HLB-positive tree anywhere in Southern California. For participants who indicated that they had groves in more than one county, we used the average distance from the centroid of the citrus production areas in the two counties indicated by the participant to the closest HLB detection. In addition, we calculated the average, minimum and maximum distance from any grove registered in the CRB citrus layer in any of the counties indicated by the participants to the closest HLB-positive tree. Centroids and distances were calculated using ArcGIS Pro (Esri, Redlands, CA, U. S. A.). Distances were then correlated with the perceived vulnerability indicated by the participants, on a numerical scale, using Spearman's rank correlation test. The coordinates of the HLB-positive trees were obtained from the database maintained by CDFA under terms of a data confidentiality memorandum of understanding between CDFA, the University of California and

CRB. Location-specific data for HLB-positive trees in California are confidential and cannot be shared in public documents.

Evaluating the impact of perceived vulnerability, information, communication and socio-economic factors on propensity to adopt, and the interdependence between practices

To take a first look at relationships between pairs of practices and between practices and explanatory factors, we calculated Spearman's rank correlation coefficients (ρ) and their associated *p*-values using the R package "Hmisc" (Harrell Jr. and Dupont, 2020). To do these analyses, responses to questions that were expressed on an ordinal scale (i.e. questions 2-4, 6-11, 13-20) were transformed to numeric, so that *very unlikely* = 1, *unlikely* = 2, *maybe* = 3, *likely* = 4, *very likely* = 5.

Because some of the recommended practices may be interdependent, either as complements or as substitutes, using univariate ordinal regression models to predict the propensity to adopt each practice separately according to the selected explanatory factors may lead to inaccurate conclusions, since they ignore potential interdependencies between practices which are the basis of an IPM approach. To address this limitation, we investigated the use of a multivariate ordinal regression model (Hirk et al., 2019). To our knowledge, this is the first time that this type of model has been used in the context of practice adoption in plant disease management. The model is based on the idea that there is a latent variable that captures the utility of adopting practices (against HLB in this case), which was assessed through ordinal ratings. This latent variable is assumed to be a linear combination of observed explanatory factors and unobserved factors captured by a stochastic error term (Greene and Hensher, 2010). Model parameters are estimated through composite likelihood methods. By using a cumulative logit link model, regression coefficients can be interpreted in terms of log odds ratios, and the error terms are assumed to jointly follow a multivariate logistic distribution (Hirk et al., 2019). By simultaneously considering the influence of explanatory factors on each of the different practices while allowing the unobserved or unmeasured factors to be freely correlated, the model estimates a correlation matrix between practices, in which the coefficients indicate the polychoric correlations between the latent utilities of each pair of practices. Polychoric correlations are defined as the correlations between each pair of latent continuous variables that have been assessed through discrete ordinal ratings (Greene and Hensher, 2010). If any correlation coefficient ρ_{ij} is significantly positive, it will indicate a complementary relationship between practices *i* and *j*. Conversely, if ρ_{ij} is significantly negative, it will indicate a substitute relationship between practices *i* and *j* (Cai et al., 2019; Hirk et al., 2019). Thus, the model can estimate which practices within the recommended portfolio are likely to be adopted together once explanatory factors have been considered.

The multivariate ordinal regression model was fitted using the R package "mvord" (Hirk et al., 2020) to the eight practices recommended by the CPDPC, for which propensity to adopt was evaluated on a 5-point ordinal scale from *very unlikely* to *very likely*. Perceived vulnerability was included in the model as a numeric explanatory factor, the propensity to stay informed and communicate with the grower liaison or to communicate with neighbors were included as numeric explanatory factors, and socio-economic factors were included as categorical or numeric explanatory factors. Categorical socio-economic factors (*role* and *management system*) were transformed to binary so that being a *grove owner* would correspond to

1 and the rest of the options would correspond to *0*. Similarly, growing citrus *conventionally* would correspond to *1* and *organically* or *both* to *0*. Ordered socio-economic factors (*acreage*, *age* and *income*) were initially included as ordered factors to test their linear effect on adoption using orthogonal polynomial coding, and once the linear effect was verified, they were transformed to numeric so that the first response category would correspond to 1, the second to 2, etc. Multicollinearity between explanatory factors was first examined through Spearman rank correlations and then checked through variance inflation factors (VIF) and condition indexes (CI), assuming that the ordinal ratings were numeric values (Daxini et al., 2018). VIFs and CIs did not indicate that there were severe multicollinearity problems in the dataset, so all factors were considered for the regression analyses. To choose the most parsimonious model, models with different explanatory factors, thresholds, regression coefficients and error structure specifications were compared using McFadden's pseudo R^2 (McFadden, 1974), a Composite Likelihood Bayesian Information Criterion (CLBIC) (Hirk et al., 2019), and likelihood ratio tests (Greene and Hensher 2010) calculated with the R package "lmtest" (Zeileis and Hothorn, 2002).

The probability of being *likely* or *very likely* to adopt each practice according to each explanatory factor was calculated using the formula of the selected multivariate ordinal regression model with the threshold parameter corresponding to the change between the categories *maybe* and *likely* and the estimated regression coefficients on the explanatory factors for each practice, fixing each factor except the one being evaluated at their mean value. With this formula, we calculated the log odds of answering *maybe* or less for each practice, which were transformed to an odds value, and then to a probability value corresponding to P (Y ≤ *maybe*). The probability of answering *likely* or *very likely* was calculated as the complement of that value, so P (Y > *maybe*)= 1 – *P* (Y ≤ *maybe*) (Greene and Hensher, 2010).

RESULTS

The perceived vulnerability to HLB has declined over the course of the epidemic, but it is correlated with an objective assessment of the likelihood of HLB detection

The first goal of this study was to assess the California citrus industry's perceived vulnerability to HLB (*i.e.*, likelihood of HLB detection in their grove in the coming year), in order to determine if it was related to their self-reported propensity to adopt the best management practices recommended by the CPDPC. We also wanted to test if the perceived vulnerability to HLB was accurate, and to compare the answers to this question with a similar survey that was conducted in 2015 (Milne et al., 2018), to test if there had been any changes in perceived vulnerability after four years of HLB spread in California.

Across the three main citrus-growing regions in California, the majority (71%) of respondents thought that it was *unlikely* or *very unlikely* that an HLB-positive tree would be detected in their grove in the next year -from July 2019 to June 2020-. Only 7.5% thought that an HLB detection was *likely* or *very likely*. The likelihood of HLB detection varied with the region of origin (P= 3.54x10^{-7} for the Kruskal-Wallis test), and pairwise comparisons between regions showed that there was a significant difference between the Valley and the Coast (P= 2.74x10^{-7} for the Wilcoxon-Mann-Whitney test) and between the Valley and SoCal (P= 4.71x10^{-5}). In the Valley, most participants (91%) believed that it was *unlikely* or *very unlikely* that there would be an

HLB detection in their grove in the next year, while fewer people believed that in the Coast (54%) or in SoCal (63%), reflecting regional differences in perceived vulnerability.

To compare the respondents' perceived vulnerability to an objective assessment of the likelihood of detecting the disease, we calculated the distance from the centroid of the citrus production areas in the county that they indicated, or the average distance between the two counties indicated, to the closest HLB positive tree confirmed by CDFA (Fig. 1, Supplementary Table 1). Distances were then correlated with the likelihood of HLB detection indicated. As expected, the participants' perception of the likelihood of an HLB detection in their grove in the coming year was negatively correlated with distance from an HLB-positive tree (ρ= -0.32, P= 0.019) Similar correlation coefficients were obtained when using the average (ρ= -0.32, P= 0.017) and maximum (ρ= -0.30, P= 0.024) distance from any grove in any of the counties indicated by the participants, but not when using the minimum distance (ρ= -0.26, P= 0.054) (Supplementary Fig. 1). Thus, in general, participants who were further away from confirmed cases of HLB thought that the probability of finding HLB in their grove was lower, and participants who were closer to HLB-positive trees thought that the probability was higher; a pattern of responses that seems to reflect a rational relationship between perceived vulnerability and actual probability of infection.

Since HLB is an invasive disease that is spreading in California, the participants' perception of the likelihood of an HLB detection in their grove was expected to influence their propensity to adopt some of the practices recommended by the CPDPC. Indeed, the likelihood of detecting HLB was positively correlated with scouting for ACP on flush (ρ= 0.29, P= 0.0002), surveying for HLB symptoms (ρ=

0.16, P= 0.04) and voluntarily testing trees and ACP (ρ= 0.26, P= 0.001). Thus, participants who perceived a higher likelihood of detecting HLB seemed to be more willing to scout, survey and test, which are three monitoring practices directly aimed at detecting HLB. Remarkably, the perceived likelihood of HLB detection was not correlated with the propensity to adopt any of the other practices.

In addition, we calculated the correlation between distance to confirmed HLB positive trees and propensity to adopt the practices recommended by the CPDPC (Table 2). All correlation coefficients were negative, indicating that participants who were further away from HLB-positive trees were less likely in general to adopt any of the practices, and those who were closer were more likely to consider them. Distance from HLB was negatively and significantly correlated with staying informed and communicating with the grower liaison, communicating with neighbors, protecting new plantings, applying repellents to the perimeter, surveying for HLB symptoms and considering the use of EDTs. On the other hand, the propensity to install barriers, scout for ACP on flush, voluntarily test or consider the use of bactericides did not significantly increase as participants got closer to HLB-positive trees.

Finally, we compared the answers obtained in 2019 with a similar survey from 2015 that was distributed during the analogous meetings in that year (Milne et al., 2018). At that time participants were asked how likely they thought it was that their groves would be infected with HLB within 5 years, which corresponded to the year 2020. The respondent sample was similar between both surveys in terms of farm size, county of origin and management system, so we believe that differences in perceived likelihood of HLB detection between the surveys might indicate changes in perception among citrus stakeholders in California. However, we note that both surveys consisted of a non-random sample of citrus stakeholders and there may have been selection bias towards people who were engaged in HLB and ACP management.

In 2015, the perceived likelihood of HLB detection by 2020 was significantly associated with the location of groves. Participants with groves in San Bernardino, Riverside, San Diego and Imperial counties (SoCal) thought they would *almost certainly* be infected by 2020; participants from the Coast thought it was *possible* or *likely*; and participants from the Central Valley thought it was *unlikely* or *possible* (Milne et al., 2018). Four years later, we noticed a shift towards thinking that HLB detection is *unlikely* or *very unlikely*. While in the 2015 survey, 26% of respondents state-wide thought that it was *unlikely* or *very unlikely* that an HLB-positive tree would be detected in their grove by 2020 (Milne et al., 2018), in the 2019 survey 71% of participants thought that an HLB detection in their grove was *unlikely* or *very unlikely* in the coming year -from July 2019 to June 2020-. Therefore, our results appear to show that the majority of the citrus industry believes that the epidemic is not progressing as fast as they thought it would four years ago.

Propensity to adopt the best management practices for HLB

The second goal of the survey was to assess the propensity to adopt the best management practices recommended by the CPDPC as they were introduced to the California citrus industry for the first time. Because these practices were envisioned as a toolkit, the ultimate intention was not only to assess the participants' propensity to adopt these practices individually, but also to determine which practices were likely to be adopted together (H5) and assess the impact that perceived vulnerability (H1), propensity to stay informed and communicate (H2, H3) and individual socio-economic factors (H4) might have on adoption. To achieve this, we first examined the responses through rank tests and correlation analyses and then used a multivariate ordinal regression model to evaluate the propensity to adopt the eight recommended practices simultaneously.

At first glance, it was clear that not all of the practices had equal probability of being adopted (Fig. 2). Overall, the majority of participants were *likely* or *very likely* to survey for HLB symptoms (74%) and scout for ACP on flush (68%), but they were *unlikely* or *very unlikely* to install physical barriers along grove perimeters (71%), to voluntarily test trees and ACP (53%) and to use EDTs (54%). Remarkably, most participants said that they were *likely* or *very likely* to stay actively informed about HLB and communicate with their grower liaison (79%) and to communicate with neighbors (65%), suggesting engagement with both formal and informal information networks.

As mentioned earlier, the eight practices were classified in three IPM categories: monitoring, prevention and suppression. Practices related to visual monitoring had a higher propensity to be adopted than preventive, suppressive and more complex monitoring practices. Because an integrated approach to HLB would involve combinations of all these practices, in subsequent analyses we sought to investigate how they were being perceived in relation to the rest of the toolkit and what factors could impact adoption.

Determinants of the propensity to adopt best management practices for HLB

To test the impact that perceived vulnerability, disposition to stay informed and communicate with the grower liaisons, disposition to communicate with neighbors and socio-economic circumstances could have on the adoption of HLB management practices, these variables were included as explanatory factors in a multivariate ordinal logistic regression model. Among several model specifications, the most parsimonious one employed a logit link function and assumed that the threshold parameters between propensity-to-adopt categories were the same for all practices and participants, that regression coefficients were specific to each practice, and that there was a general correlation structure between the error terms (Hirk et al., 2019). The participants' perceived vulnerability to HLB, their propensity to stay informed and communicate with the grower liaison, their propensity to communicate with neighbors and farm size were included as numeric explanatory factors. In addition, we included an interaction term between perceived vulnerability and propensity to stay informed and communicate, to test if providing information to growers fostered adoption under different vulnerability scenarios. Because differences in perceived vulnerability were associated with the region of origin and there was a strong correlation between perceived vulnerability and distance from HLB-positive trees, we decided to discard *region* and *distance from HLB* as explanatory factors, choosing to focus on perceived vulnerability. The other explanatory factors were also discarded during model selection because they did not significantly improve model fit, according to likelihood ratio tests (Supplementary Table 2). The most parsimonious model had a CLBIC of 26506 and a McFadden's adjusted pseudo R^2 of 0.0291 (df= 583.8), and all the explanatory factors had a significant impact on at least one practice. This model did not have significantly lower fit than the model with all explanatory factors, and it significantly improved fit compared with models with fewer explanatory factors (P= 0.0032), as well as the model with no predictors ($P< 2.2\times10^{-16}$), which had a CLBIC of 26817 and an adjusted pseudo R^2 of -0.085 (df= 81.73).

In the most parsimonious model, there was a significant effect of perceived vulnerability, disposition to stay informed and communicate with both liaisons and neighbors and farm size on one or more practices, and a significant interaction between perceived vulnerability and propensity to stay informed and communicate with the liaison (Fig. 3, Supplementary Table 3).

As hypothesized, the estimated likelihood of HLB detection in a citrus grove in the coming year (*perceived vulnerability*) had a positive impact on the participants' propensity to adopt most of the HLB management practices (H1). This indicates that participants who felt more vulnerable to HLB had higher odds of being more likely to protect their citrus groves, in line with the Protection Motivation Theory. The exception was the use of EDTs, for which there was no apparent relationship with perceived vulnerability. The coefficients were positive and significant with 90% confidence for scouting for ACP, protecting replants, treating grove perimeters and using bactericides (Fig. 3). Therefore, for a one unit increase in perceived vulnerability, the odds that someone would be more likely to protect new citrus plantings were 4.7 [exp(1.55)] times higher, 3.8 higher for scouting for ACP on flush, 2.7 times higher for treating the grove perimeter and 2.8 times higher for using bactericides. Interestingly, people who felt more vulnerable to HLB did not have significantly higher odds of testing their trees or surveying for HLB symptoms, suggesting that they were not willing to put more effort into detecting the disease.

As expected, the intention to stay informed and communicate with the grower liaison had a positive impact on the propensity to adopt all of the practices, and it was significant in most cases (H2). Participants who were more likely to seek information and be engaged with the regional coordinators of the HLB control program had significantly higher odds of adopting monitoring practices such as scouting for ACP and surveying for HLB symptoms, preventive practices such as protecting new plantings, installing barriers around citrus groves and applying pesticides or repellents to the perimeter, as well as using bactericides. This confirms that the formal network that was set up by the CPDPC might be effective in promoting the adoption of most practices. However, more engagement with the control program did not lead to significantly higher odds of testing or using EDTs, indicating that alternative strategies might be required to foster the adoption of these two tools.

Moreover, we detected a significant interaction between the participants' intention to stay informed and communicate with the grower liaison and their perceived vulnerability to HLB on the adoption of two practices. This indicates that the benefits of promoting HLB management through the CPDPC outreach network might depend on how vulnerable citrus growers feel to HLB, and therefore on the stage of the HLB epidemic. Positive regression coefficients on the interaction term would indicate a synergistic effect in which higher vulnerability and more information and communication act together to encourage further adoption than any of the two explanatory factors alone, while negative coefficients would indicate that the two factors may act against each other. Neither of the two positive interaction effects were significant, but two of the six negative ones were. This suggests that the odds of protecting replants or applying pesticides and repellents to the perimeter might only increase with information and interaction with the grower liaisons under low perceived vulnerability to HLB, and the trend may change under higher vulnerability scenarios, as will be further explored in the next section.

The propensity to adopt some HLB management practices was also impacted by the intention to communicate with neighbors (H3), but the sign of this impact varied for each practice. For most practices it was positive, meaning that participants who were more likely to communicate with neighbors had higher odds of adoption, but it was only significant for two practices. A one unit increase in the intention to communicate with neighbors led to 1.6- and 1.33-times higher odds of surveying for HLB symptoms and using EDTs, indicating that informal networks might be a pathway to promote the adoption of these tools.

In terms of the impact that the participants' socio-economic circumstances could have on their propensity to adopt HLB management practices, farm size was the only significant predictor of adoption, giving limited support to H4. Participants with larger citrus operations had significantly higher odds of being more likely to scout for ACP and test, but they had lower odds of taking extra measures to protect new plantings. In fact, for every unit increase in the farm size category, participants had 0.75 times the odds of being more likely to protect replants. Once perceived vulnerability to HLB and the intentions to stay informed and communicate were incorporated into the multivariate ordinal logistic regression model, the participants' *role* in citrus production, their *age*, their *management system* and the percentage of their *income* coming from citrus were not significant predictors of their propensity to adopt any of the HLB management practices.

Estimating the probability of being likely or very likely to adopt the best management practices for HLB

The ultimate goal of using a regression model in this type of study is to be able to make predictions about the adoption of HLB management practices according to the variables that were identified from the existing literature and measured in the study. To facilitate the interpretation of the results, we calculated the predicted probabilities of being *likely* or *very likely* to adopt each of the practices in relationship to each explanatory factor, while keeping the rest of the factors at their mean value (Supplementary Fig. 2).

In particular, we were interested in examining the interaction between perceived vulnerability and the intention to stay informed and communicate with the grower liaison, because the significant regression coefficients on the interaction term suggested that the benefits of informing citrus stakeholders about the different practices might vary depending on the stage of the HLB epidemic. Indeed, as Fig. 4 shows, the probability of being *likely* or *very likely* to adopt HLB management practices varies depending on the intention to stay informed and communicate with the grower liaison, represented by the slopes of the different practices, and it also varies depending on the perceived vulnerability to HLB, represented by the different panels. But more importantly, the effect of information and communication on the adoption of some of these practices varies depending on the HLB scenario; this can be seen in the variation in the sign of the slopes of some practices across panels.

For example, in the top left panels in Fig. 4, when HLB detection is perceived to be *unlikely* or *very unlikely,* staying informed and communicating with the grower liaison tends to have a positive effect on the adoption of most practices. When HLB detection is perceived as *very unlikely*, the probability of surveying for symptoms increases from about 30% for people who are *very unlikely* to seek information and interact with the liaison to about 75% for people who are *very likely* to do it. However, once HLB detection is perceived to be *likely* or *very likely*, the effect of communication on adoption switches for several practices, and significantly for protecting replants and applying pesticides or repellents to the perimeter. Under high vulnerability to HLB, the adoption of these two practices drops from 80-90% for people who are *very unlikely* to stay informed and communicate with the liaison to 20-30% for people who are *very likely*. Remarkably, the positive effect of communication on the adoption of surveys, testing and EDTs tends to remain stable across the HLB scenarios, encouraging the CPDPC to keep promoting the adoption of these monitoring practices.

Interdependence in the propensity to adopt the best management practices for HLB

A preliminary calculation of rank correlations between practices suggested that several of them were likely to be adopted together, particularly those belonging to the same IPM category (Supplementary Table 4). However, rank correlations can only estimate the strength and direction of the monotonic relationship between two variables (*i. e.,* if the propensity to adopt two variables increases or decreases in parallel). One of the strengths of using a multivariate ordinal regression model is that it allows the estimation of the polychoric correlations, which indicate the underlying propensity to adopt each pair of practices once explanatory factors have been considered (Greene and Hensher, 2010).

The multivariate ordinal regression model indicated that there were several significant polychoric correlations between practices (Fig. 5, Supplementary Table 5), suggesting that the propensity to adopt different practices is interdependent, as hypothesized (H5). No significant negative correlations were found, indicating that most practices were perceived as complementary, which supports the idea of promoting these as a management toolkit. The two practices that had the highest acceptance (Fig. 2), visually inspecting for HLB symptoms and scouting for ACP, had a very high correlation and emerged at the core of the practice adoption network (Fig. 5). Considering that these two practices have been promoted for the longest period of time, are similar to other monitoring protocols that citrus stakeholders routinely follow, and they can be implemented simultaneously while inspecting citrus groves, it was reasonable that they would be highly accepted and highly correlated, but we were surprised to find that they were not significantly correlated with any other practice, particularly the two other monitoring practices (testing and EDTs).

By contrast, practices that seemed to have low acceptance, such as using barriers, protecting replants, testing and using EDTs were highly correlated. These correlations show that practices in the same IPM category are perceived as complementary, but also that there is another dimension that relates them across categories that was not measured in our model. Additionally, the strong correlation between treating the grove perimeters and voluntarily testing suggests that these two practices may be perceived as two components of a strategy to prevent ACP from entering citrus groves and to detect the presence of *C*Las as soon as possible, which was actually suggested during the presentation of the *Voluntary Grower Response Plan*. The use of bactericides, which was not officially recommended by the CPDPC, had very low acceptance and it was only correlated with the use of EDTs and taking extra measures to protect new plantings, so it is unclear how California growers might integrate bactericides into HLB management.

DISCUSSION

The adoption of management practices for invasive plant diseases has been an understudied topic in plant pathology. Early surveys conducted by our group and collaborators in 2015 showed that risk perception and trust in control options were key factors in the decision to join the area-wide management program for HLB in California (Milne et al., 2018). At that time, suppressing the ACP population, removing HLB-positive trees and using certified plant material were the main management practices recommended to the growers to prevent the spread of HLB (Gottwald, 2010). Four years later, these measures seem to have been at least somewhat effective. HLB-positive trees are still confined to residential properties in the Los Angeles metropolitan area, but the number of trees detected increases weekly. As the portfolio of management practices expanded and the *Voluntary Grower Response Plan for Huanglongbing* was introduced to the citrus industry, it was deemed necessary to assess the propensity to adopt the recommended practices in order to develop a targeted outreach program that could foster adoption.

In this study, participants were asked about their perception of the likelihood of an HLB detection in their grove in the coming year (July 2019 - June 2020), assuming that it could be one of the key factors prompting them to adopt management practices, in line with the human disease literature (Gaube et al., 2019; Sheeran et al., 2014). Despite some regional differences, the vast majority of participants believed that an HLB detection was unlikely. This low perceived vulnerability was very surprising, especially considering that the ACP is widespread in Southern and Coastal California, and that *C*Las-positive trees and ACP had been detected close to commercial citrus groves in the counties of Riverside and San Bernardino. However, one year after the survey, by the end of June 2020, HLB-positive trees had still not been detected in any commercial groves, proving that the participants' perception of the likelihood of HLB detection was not inaccurate. In fact, it was negatively correlated with distance from confirmed HLB-positive trees, providing evidence that they were aware of their proximity to infected trees.

Possible explanations for the widespread low perceived vulnerability to HLB could be a general belief that the control program has been effective at preventing HLB spread, for example by covering citrus trucks with tarps to reduce ACP dispersal (McRoberts and Deniston-Sheets, 2021); that the Mediterranean climate in California is not optimal for ACP and/or *C*Las and is thus hindering spread (Narouei-Khandan et al., 2016); or that the 1-year horizon in the question about the likelihood of HLB detection was too short. We extended the time horizon in a follow-up survey in Ventura County in October of 2019, in which we asked participants about the likelihood of HLB detection in their groves in 1 year and in 5 years (until October of 2024). Interestingly, while 60% of participants believed that it was *unlikely* or *very unlikely* that HLB would be detected in their grove in 1 year, only 16% of participants believed that for 5 years. The remaining 42% thought that it was *likely* or *very likely*, and 42% chose *maybe*, denoting considerable uncertainty about the future (*unpublished data*).

Immediately after the presentation of the *Voluntary Grower Response Plan for Huanglongbing,* our survey showed that not all of the HLB management practices are equally likely to be adopted. While participants were in favor of surveying for HLB symptoms or scouting for ACP, they were reluctant to install barriers, test trees or ACP, or consider the use of EDTs. Through the use of a multivariate ordinal regression model, we were able to gain insight into the heterogeneity in adoption, enhancing our understanding of the influence of perceived vulnerability, intentions to stay informed and communicate and socio-economic factors on adoption, and estimating which practices were likely to be adopted together.

This type of model, which was originally developed in a financial context to be freely implemented in R (Hirk et al., 2019), has great potential for practice adoption studies. First, it avoids the simplification of merging different practices into a single adoption score, which has been criticized in the past (Puente et al., 2011). Second, it also avoids evaluating each practice in isolation, which may lead to biased and inefficient estimates (as explained in Kassie et al., 2013). Third, it can be used to analyze surveys with ordinal answers, which provide a finer scale to measure propensity to adopt than binary answers that would be analyzed with multivariate probit models (Cai et al., 2019).

In terms of the measured predictors of adoption, our results support the hypothesis that risk perception is a driver of management actions against invasive plant diseases, as proposed by the Protection Motivation Theory in the context of human diseases (Rogers, 1975), and by pioneering studies focused on plant pests (Heong and Escalada, 1999). The multivariate ordinal logistic regression model indicated that perceived vulnerability to HLB had a positive effect on the probability of scouting for ACP on flush, protecting replants, treating grove perimeters and using bactericides. However, the impact of perceived vulnerability was significant only for these four practices, and inconsistent relationships between risk perception and practice adoption have been observed in other studies of invasive plant diseases (Breukers et al., 2012; Mankad et al., 2019). Therefore, the evidence collected to date suggests that cross-sectional studies that predict the adoption of management practices with risk perception as the core predictor might be incomplete, and future longitudinal studies that consider risk perception and practice adoption at several time points (Raude et al., 2019) and include other explanatory factors might be more useful.

In fact, the intention to stay informed and communicate with the grower liaisons had a positive impact on the adoption of most practices, suggesting that the information network that was set up by the CPDPC might be a relevant factor in promoting adoption. Remarkably, very few participants said that they didn't know who their grower liaison was, and 79% were *likely* or *very likely* to communicate with them, proving their recognition by the community. However, the interaction between perceived vulnerability and staying informed and communicating with the liaison suggests that the benefits of promoting HLB management through the CPDPC outreach network might depend on how vulnerable citrus growers feel to HLB, and therefore on the stage of the HLB epidemic.

People who were more likely to communicate with neighbors had a higher propensity to adopt most practices, confirming the importance of informal communication networks on adoption, even though the effect was only significant for visual surveys and EDTs. Considering that EDTs were negatively impacted by the perceived vulnerability to HLB and not significantly impacted by staying informed and communicating with the grower liaison, neighbor-to-neighbor communication might be a way to promote the adoption of these innovative tools. Indeed, previous studies have shown that growers turn to other growers for information about disease management practices (Hillis et al., 2017; Maclean et al., 2019; Sherman et al., 2019), and participatory trials have been successful in promoting the adoption of HLB management practices in Texas by letting the growers experience the benefits themselves and spread the word in their communities (Sétamou, 2020).

Farm size was identified as the main socio-economic factor that could impact the adoption of HLB management practices. As the size of the citrus operations increased, there was a positive effect on most practices, which is in line with previous literature about the adoption of other agricultural practices (Prokopy et al., 2019). This effect was significant for scouting for ACP and testing. However, larger citrus operations had a lower probability of taking extra measures to protect new plantings, probably because of the cost associated with these measures (Alferez et al., 2019).

Remarkably, the participants' role in citrus production, their age, their management system and the percentage of their income coming from citrus did not have a significant effect on the propensity to adopt HLB management practices. In fact, initial rank tests only showed that PCAs were more in favor of using EDTs; that organic growers were less likely to apply extra pesticides or repellents to the perimeter of groves; and that participants who obtained 26-50% of their income from citrus were less likely to communicate with neighbors, while those who obtained 51-75% of their income from citrus were more likely to do it. Although these factors could not be used to predict adoption, the observations might still be useful for the outreach program. PCAs might be more inclined to use EDTs because they often manage multiple operations and need to make rapid, evidence-based decisions, so they could be targeted by the outreach program and the companies providing EDT services to promote these tools among the citrus community. As PCAs play an increasingly crucial role in advising growers (Eanes et al., 2019; Hillis et al., 2016), outreach activities and workshops aimed specifically at this group could be very beneficial. One of the reasons why organic growers might be less willing to treat grove perimeters is that there are only a few products approved for this use by organic certification programs. Finally, the peculiar effect of income on communication with neighbors is hard to explain, but no other association was found between income dependency on citrus and propensity to adopt, contrary to previous studies on other invasive plant diseases (Mankad et al., 2019).

In terms of the interdependence between practices, the multivariate ordinal logistic regression model indicated that the propensity to adopt all of the practices was positively correlated, giving support to the idea of a management toolkit. The two monitoring practices that had been promoted from the beginning of the HLB epidemic, scouting for ACP and surveying for symptoms, were highly accepted and highly correlated, providing evidence of the citrus industry's commitment to monitor the vector and the disease. However, they were not correlated with the other two monitoring practices (tests and EDTs), showing a disconnect between visual inspections and more accurate and earlier diagnostic tests. In fact, tests and EDTs were the only two practices not significantly impacted by the intention to stay informed and communicate with the grower liaison, suggesting that they may be harder to promote through the CPDPC network. Voluntary testing in particular seemed to have low acceptance and not be correlated with many practices. This may be due to the uncertainty associated with the consequences of a positive test result and fear of quarantine restrictions, as a *C*Las-positive qPCR test on leaf material is considered a regulatory positive by the CDFA and it triggers mandatory action (i.e., tree removal and quarantine), while a *C*Las-positive ACP or a positive EDT test do not trigger mandatory action. One year after this study, the use of one type of EDT

(Gottwald et al., 2020) has started in the Coast production area and a comparable approach to detect ACP is being considered by the CPDPC, so clarifying the test options available, how they could be integrated in an HLB management plan, and clearly explaining the consequences of a positive result should be a priority for the outreach program to improve surveillance efforts.

Interestingly, some practices that seemed to have low acceptance, such as testing, using EDTs, installing barriers and protecting replants were highly correlated. Two possible reasons for the low acceptance and correlations between these monitoring and preventive practices could be their novelty and cost, which were not measured in our survey. Previous studies have shown that growers tend to adopt practices if the benefits clearly outweigh the costs (Lubell et al., 2011), but adoption is limited for practices with benefits that are difficult to observe or extend over long periods of time (Rogers, 2010). Although we did not ask any specific questions about perceived cost, installing barriers would be costly, particularly for groves with extensive perimeters, and EDTs were considered so new that the citrus industry decided not to include them in the *Voluntary Grower Response Plan*. Neither were bactericides included, and they had very low acceptance and were only correlated with the use of EDTs and taking extra measures to protect new plantings, again suggesting that novelty might be a relevant factor for adoption. In addition, bactericides have provided mixed results in other citrus-growing areas (Blaustein et al., 2017) and they raise concerns among consumers about antibiotic residues potentially present on fruit (Jacobs, 2017; Jacobs and Adno, 2019), so it is unclear how the use of bactericides will unfold as the HLB epidemic progresses in California.

Overall, we believe that future studies about the adoption of plant disease management practices would benefit from the explicit incorporation of behavioral models. One such model is the theory of planned behavior (TPB) (Ajzen, 1991), which has been widely used to explain practice adoption in agriculture (Borges et al., 2019; Daxini et al., 2018), with some pioneering applications in plant disease management (Breukers et al., 2012). The TPB proposes that the *attitude toward the behavior* (the degree to which a person has a favorable or unfavorable evaluation of the behavior), *subjective norms* (perceived social pressure to perform the behavior) and *perceived behavioral control* (confidence in the ability to perform the behavior) collectively determine people's behavioral intentions, and ultimately their behavior (Ajzen, 1991). Therefore, asking stakeholders about these three factors in relation to any particular disease management practice might provide better understanding of their ultimate intentions (Janssen et al., 2020). In fact, the finding that "trust in control options" had a higher impact on the success of a control campaign against an invasive plant pathogen than risk perception (Milne et al., 2020) is direct evidence of the importance of *perceived behavioral control* for practice adoption and ultimately successful control. Similarly, "values placed on social approval and peer comparisons" (i.e., *perceived norms*) were key motivating factors to adopt management actions during the first months after the detection of Panama TR4 in Australia (Mankad et al., 2019). In our case, it was hard to assess the citrus industry's *attitudes*, *perceived norms* and *perceived behavioral control* about HLB management practices as they were hearing about some of them for the first time, but once stakeholders become more familiar with these practices, we believe that future studies aimed at understanding adoption drivers may benefit from focusing more on this type of factor and a careful examination of the relationship between risk perception and protective behavior over time (Gaube et al., 2019), rather than on individual socio-economic factors that should be used as controls but appear to yield only weak explanatory models of self-reported propensity to adopt management practices.

CONCLUSIONS

When an invasive plant disease is introduced in a new territory, management efforts have to be mobilized and coordinated at different scales to face the emerging threat, usually under conditions of high uncertainty and lack of previous experience. Individuals who could potentially be affected by the disease need to react quickly and adopt management practices in a coordinated manner to effectively prevent spread. Under these circumstances, it becomes crucial to understand what factors might drive or prevent the adoption of management practices, and how outreach efforts could be targeted to provide a more effective response to the invasive disease. This study contributes to this understanding by assessing the California citrus industry' propensity to adopt a toolkit of best management practices to prevent the spread of HLB once it was no longer possible to eradicate it, but before it had spread to commercial groves. Our results show that perceived vulnerability to HLB, intentions to stay informed and communicate with formal and informal networks and farm size could be relevant factors for adoption, and that the adoption of different management practices is interdependent. Further studies that address the stakeholders' attitudes towards the practices, their perceived norms and their perceived behavioral control at different points in time will likely enhance our understanding of the drivers of protective action against invasive diseases, contributing to ensure the sustainability of crop production under HLB and other emergent plant diseases.

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TABLE 1: Socio-economic characteristics of the survey respondents (n = 160*).

Survey item	Responses	Percentage of total
Role in citrus production		
Grove Owner	68	43%
Ranch Manager	27	17%
PCA	24	15%
PCO	3	2%
Other	31	19%
Farm size		
< 5 acres	24	15%
5 – 25 acres	30	19%
26 – 100 acres	21	13%
101 – 500 acres	24	15%
> 500 acres	61	38%
Age		
<35 years	27	17%
35 - 50 years	29	18%
51 – 65 years	57	36%
> 65 years	47	29%
Region		
Coast	61	38%
SoCal	35	22%
Valley	64	40%
Management system		
Conventional	113	71%
Organic	7	4%
Both	39	24%
Income from citrus		
< 25%	58	38%
26 - 50%	20	13%
51 - 75%	21	13%
76 - 100%	54	34%

*Although the data set that was used for the analyses contained the responses from 160 participants, not all of them answered to every socio-economic question.

TABLE 2: Spearman rank correlations between the propensity to adopt the recommended practices and the average distance from the centroid of the citrus acreage in each county or counties to the closest tree confirmed to be HLB-positive by the CDFA (see Fig. 1).

Question	Correlation coefficient	*P*
Perceived vulnerability	-0.40	1.12E-07
Stay informed and communicate with liaison	-0.22	0.005
Communicate with neighbors	-0.18	0.022
Protect new plantings	-0.09	0.286
Barriers	-0.19	0.018
Repellents to perimeter	-0.05	0.559
Scout for ACP on flush	-0.39	4.40E-07
Survey for HLB symptoms	-0.28	3.04E-04
Test (qPCR)	-0.16	0.044
EDTs	-0.17	0.038
Bactericides	-0.10	0.215

Figure 1: Distance from the centroid of the citrus acreage in each county to the closest HLB-positive tree detected by CDFA. The areas shaded in black represent the citrus production areas according to the Citrus Research Board (CRB) database (R. Dunn, *personal communication*). The black dots represent the coordinates of the centroid of those citrus production areas in each county. The blue dashed lines represent the distance from the centroids to the closest HLB-positive tree (actual distances are shown in Supplementary Table 1). The coordinates of the HLB-positive trees were obtained from the Citrus Pest and Disease Prevention Program (CPDPP) database maintained by the California Department of Food and Agriculture (CDFA) under terms of a data confidentiality memorandum of understanding between CDFA, the University of California and CRB. The perimeter of the HLB quarantine zone at the time of the survey is shown in blue (R. Johnson, personal communication). The counties where survey participants had citrus groves have been labelled and colored in shades of orange according to the total citrus acreage harvested in each county in the year 2018 (Fresno CAC, 2019; Imperial CAC, 2019; Kern CAC, 2019; Madera CAC, 2019; Riverside CAC, 2019; San Bernardino CAC, 2019; San Diego CAC, 2019; Santa Barbara CAC, 2019; Tulare CAC, 2019; Ventura CAC, 2019).

Figure 2: Reported propensity to adopt the best management practices for HLB. The practices assessed in the survey are shown on the y axis, ordered from highest (top) to lowest (bottom) percentage of *likely* and *very likely.* The percentage of responses to each question was calculated on a total number of responses indicated between parentheses under each practice. The legend at the top shows the correspondence between the response chosen and the colors on the plot.

Figure 3: Confidence intervals of the regression coefficients estimated by the multivariate ordinal regression model. The x axis represents the values of the regression coefficients. The y axis identifies the explanatory factor that the coefficients correspond to. The symbols correspond to the value of the regression coefficient on each explanatory factor for each practice estimated by the multivariate ordinal regression model, and the whiskers represent the 90% confidence interval around the estimated value. The shape of the symbols represents the integrated pest management (IPM) category that each practice was classified under, and the colors represent the practice according to the legend on the right. Practices have been ordered from highest to lowest propensity to adopt (percentage of *likely* and *very likely*), according to Fig. 2.

Figure 4: Probability of being *likely* or *very likely* to adopt the best management practices for HLB according to the perceived vulnerability to HLB and the propensity to stay informed and communicate with the grower liaison. The practices were colored according to the legend on the right.

Figure 5: Interdependence in the propensity to adopt the best management practices for HLB, as estimated by the multivariate ordinal logistic regression model. The nodes in the network correspond to each practice, with different shapes for the integrated pest management (IPM) category each practice belongs to, according to the legend on the right. The width and color of the edges between nodes correspond to the correlation coefficient between practices estimated by the multivariate ordinal logistic regression model (Supplementary Table 5).

Supporting Material (e-Xtra)

Supplementary text 1: Survey questionnaire

1. What is your main role in citrus production?

a. Grove owner

b. Ranch manager

c. Pest Control Adviser (PCA)

d. Pest Control Operator (PCO)

e. Other

2. How many acres of citrus do you grow or manage?

a. <5 acres

b. 5-25

c. 26-100

d. 101-500

e. >500

3. What age group are you in?

a. <35 years

b. 35-50

c. 51-65

d. >65 years

4. Where are your groves located? (click all that apply)

a. Fresno

b. Imperial

c. Kern

d. Madera

e. Riverside

f. San Bernardino

g. San Diego

h. Santa Barbara

i. Tulare

j. Ventura

5. How do you grow citrus?

a. Conventionally

b. Organically

c. Both

6. What percentage of your income comes from citrus?

a. 0-25%

b. 26-50%

c. 51-75%

d. 76-100%

7. How likely do you think it is that an HLB-positive tree will be detected in your grove in the next year?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

8. How likely is it that you will stay informed about HLB and actively communicate with your grower liaison?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

f. I don't know who my liaison is

9. How likely is it that you will be actively communicating with your neighbors (growers and homeowners)?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

10. How likely is it that your grove will be regularly scouted for ACP nymphs on flush?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

14. If you plant citrus, how likely is it that you will adopt extra measures such as bags or repellents to protect them?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

15. How likely is it that you will install physical barriers such as mesh or windbreaks around your grove(s)?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

16. How likely is it that you will apply extra pesticides or repellent to the perimeter of your grove? (beyond what you are asked to do)

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

17. How likely is it that you, your staff or PCA will conduct visual surveys for HLB symptoms? a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

f. I don’t know how to do this

18. How likely is it that you will have your trees and psyllids tested beyond what CDFA will be testing (perimeter only within 400 meters of a positive tree or nymph)?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

19. How likely is it that you will consider using EDTs in your grove(s) to get a better picture of where the disease might be?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

20. How likely is it that you will consider the application of bactericides in your grove(s)?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

f. I would need more information

Supplementary Table 1: California counties represented in the survey and distances to confirmed HLB-positive trees

Counties	Region assigned	Number of respondents	Mean distance from centroids (km)	Mean distance from groves (km)	Minimum distance from groves (km)	Maximum distance from groves (km)
Fresno	Valley	4	312	312	284	381
Fresno, Kern	Valley	1	240	240	121	381
Fresno, Madera	Valley	1	333	333	284	383
Fresno, Tulare	Valley	7	286	286	202	381
Fresno, San Bernardino	SoCal	1	166	168	6	381
Imperial	SoCal	2	198	198	164	293
Imperial, Riverside	SoCal	2	126	130	0.3	293
Imperial, San Diego	SoCal	2	143	142	38	293
Kern	Valley	8	168	168	121	243
Kern, Riverside	SoCal	1	111	115	0.3	260
Kern, Tulare	Valley	9	214	214	121	303
Madera	Valley	3	354	354	344	383
Madera, Tulare	Valley	3	307	307	202	383
Riverside	SoCal	13	54	62	0.3	260
Riverside, San Diego	SoCal	5	71	74	0.3	260
Riverside, Ventura	SoCal	1	71	75	0.3	260
San Bernardino	SoCal	1	20	24	6	178
San Bernardino, San Diego	SoCal	1	54	55	6	178
San Bernardino, Ventura	SoCal	1	54	56	6	178
San Diego	SoCal	3	87	85	38	157
San Diego, Santa Barbara	SoCal	1	123	121	38	225
San Diego, Tulare	SoCal	1	173	172	38	303

Santa Barbara	Coast	4	158	158	124	225
Santa Barbara, Ventura	Coast	6	123	123	64	225
Tulare	Valley	28	259	259	202	303
Tulare, Ventura	Coast	4	174	173	64	303
Ventura	Coast	47	88	87	64	124

Note: "Mean distance from centroids" is the distance from the centroid of the citrus-production area in the county indicated by the participant (or the average of the distance from the centroids of the production areas in the two counties indicated by the participant) to the closest HLB-positive tree. "Mean distance from groves" is the mean distance of any grove recorded in the CRB database in the county indicated by the participant (or the mean of the means of the groves in the two counties indicated) to the closest HLB-positive tree. "Minimum" is the minimum distance to the closest HLB-positive tree from any grove in the county/ies indicated by the participants. "Maximum" is the maximum distance to the closest HLB-positive tree from any grove in the county/ies indicated by the participants.

Supplementary Table 2: Model selection

Model	risk	com	neigh	acre	age	role	prodtype	income	risk*com	com*neigh	Explanatory factors with a significant regression coefficient on at least one practice	McFadden's pseudo R2	df	Loglik	CLBIC	LR test (Prob>chi2)
1	x	x	x	x	x	x	x	x	x	x	-	0.038	2411	-10480	32974	1 with respect to 2
2	x	x	x	x	x	x	x	x	x		-	0.034	1799	-10529	30021	1 with respect to 3
3	x	x	x	x	x	x	x	x			risk	0.027	1377	-10614	28089	
4	x	x	x	x					x	x	acre, com, com*neigh	0.034	740	-11699	27153	0.734 with respect to 5
5	x	x	x	x	x				x		risk, com, neigh, risk*com	0.031	742	-11745	27254	1 with respect to 6
6	**x**	**x**	**x**	**x**					**x**		**risk, com, neigh, acre, risk*com**	**0.029**	**584**	**-11772**	**26506**	**0.0032 with respect to 8**
7	x	x	x	x						x	risk, acre, com*neigh	0.032	589	-11740	26471	5.444e-08 with respect to 8
8	x	x	x	x							risk, com, neigh, acre	0.023	456	-11859	26034	0.023 with respect to 9
9	x	x	x								risk, com, neigh	0.017	342	-11932	25601	0.022 with respect to 11
10	x	x		x							risk, com, acre	0.012	244	-11930	25594	3.571e-13 with respect to 11
11	x	x									risk, com	0.012	244	-12006	25251	< 2.2e-16 with respect to 12
12	x										risk	-0.011	160	-12290	25394	< 2.2e-16 with respect to 15

13	x		com	0.004	160	-12113	25038	< 2.2e-16 with respect to 15
14		x	neigh	-0.001	161	-12169	25155	< 2.2e-16 with respect to 16
15			-	-0.085	82	-13202	26818	

Note: The first three models were fitted to a smaller data set (n=146) that had answers to all explanatory factors. The rest of the models (4-15) were fit to a larger data set (n=160) that had answers to the explanatory factors included. The factor *risk* corresponds to perceived vulnerability; *com* corresponds to staying informed and communicating with the grower liaison; *neigh* corresponds to communicating with neighbors; *acre* corresponds to farm size; *prodtype* corresponds to the management system (conventional, organic or both); *risk*com* corresponds to an interaction term between perceived vulnerability and staying informed and communicating with the grower liaison; and *com*neigh* corresponds to an interaction term between staying informed and communicating with the grower liaison and communicating with neighbors. The probabilities reported in the LR test column correspond to the probability of the test statistic from the likelihood ratio test being larger than the critical value to reject the null hypothesis that all the regression coefficients are zero with 95% confidence, according to a chi-squared distribution with degrees of freedom equal to the number of parameters that are constrained (removed) between the two models being compared. The LR test is used to test if there is a significant improvement of fit by adding additional parameters to a model

Supplementary Table 3: Regression coefficients from the multivariate ordinal logistic regression model

Explanatory factor	Practice	Estimate	Lower CI	Upper CI	Std. Error	z value	*P*
Perceived vulnerability	Scouting for ACP	1.340	0.142	2.539	0.729	1.839	0.066
	Protecting replants	1.550	0.651	2.453	0.548	2.833	0.005
	Barriers	0.845	-0.018	1.708	0.525	1.610	0.107
	Treating perimeter	0.996	0.051	1.942	0.575	1.734	0.083
	Surveying for symptoms	0.673	-0.180	1.525	0.518	1.298	0.194
	Testing	0.074	-0.694	0.842	0.467	0.159	0.874
	EDTs	-0.167	-0.930	0.595	0.464	-0.361	0.718
	Bactericides	1.030	0.088	1.963	0.570	1.799	0.072
Propensity to stay informed and communicate with the grower liaison	Scouting for ACP	0.627	0.233	1.020	0.239	2.620	0.009
	Protecting replants	0.871	0.480	1.262	0.238	3.662	0.000
	Barriers	0.428	0.025	0.830	0.245	1.746	0.081
	Treating perimeter	0.572	0.160	0.984	0.250	2.286	0.022
	Surveying for symptoms	0.570	0.198	0.943	0.226	2.519	0.012

	Testing	0.117	-0.266	0.500	0.233	0.504	0.614
	EDTs	0.309	-0.069	0.687	0.230	1.345	0.179
	Bactericides	0.466	0.097	0.835	0.224	2.075	0.038
Propensity to communicate with neighbors	Scouting for ACP	0.054	-0.210	0.318	0.161	0.336	0.737
	Protecting replants	-0.062	-0.342	0.219	0.171	-0.362	0.717
	Barriers	-0.240	-0.514	0.035	0.167	-1.435	0.151
	Treating perimeter	0.131	-0.157	0.419	0.175	0.749	0.454
	Surveying for symptoms	0.476	0.211	0.740	0.161	2.958	0.003
	Testing	0.254	-0.033	0.540	0.174	1.457	0.145
	EDTs	0.287	0.022	0.553	0.161	1.780	0.075
	Bactericides	0.093	-0.178	0.363	0.164	0.564	0.573
Citrus acreage	Scouting for ACP	0.227	0.012	0.442	0.131	1.734	0.083
	Protecting replants	-0.285	-0.504	-0.066	0.133	-2.141	0.032
	Barriers	0.103	-0.115	0.321	0.133	0.777	0.437
	Treating perimeter	0.085	-0.141	0.310	0.137	0.618	0.537
	Surveying for symptoms	0.020	-0.190	0.230	0.128	0.155	0.877

	Testing	0.232	0.028	0.437	0.124	1.867	0.062
	EDTs	0.000	-0.206	0.206	0.125	0.000	1.000
	Bactericides	-0.095	-0.298	0.108	0.123	-0.770	0.441
*Perceived vulnerability * Propensity to stay informed and communicate with the grower liaison*	Scouting for ACP	-0.183	-0.451	0.084	0.163	-1.127	0.260
	Protecting replants	-0.311	-0.516	-0.107	0.124	-2.508	0.012
	Barriers	-0.143	-0.350	0.064	0.126	-1.136	0.256
	Treating perimeter	-0.242	-0.460	-0.024	0.133	-1.826	0.068
	Surveying for symptoms	-0.090	-0.291	0.112	0.123	-0.730	0.466
	Testing	0.042	-0.130	0.214	0.105	0.404	0.686
	EDTs	0.057	-0.116	0.230	0.105	0.543	0.587
	Bactericides	-0.170	-0.378	0.037	0.126	-1.349	0.178

Note: 90% confidence interval (CI), standard error (Std. error)

Supplementary Table 4: Correlation coefficients and standard errors (between parentheses) in the adoption of the eight practices recommended for HLB, estimated by the multivariate ordinal logistic regression model.

	Scouting for ACP	Treating perimeter	Testing	Protecting replants	EDTs	Bactericides	Barriers
Surveying for symptoms	0.375** (0.119)	0.098 (0.146)	0.054 (0.14)	0.124 (0.144)	0.033 (0.149)	0.144 (0.135)	-0.007 (0.145)
Scouting for ACP		0.017 (0.138)	0.056 (0.143)	0.083 (0.143)	0.018 (0.149)	0.121 (0.143)	0.046 (0.163)
Treating perimeter			0.389*** (0.108)	0.463*** (0.113)	0.057 (0.16)	0.188 (0.132)	0.286* (0.142)
Testing				0.221. (0.132)	0.328* (0.128)	0.061 (0.123)	0.046 (0.134)
Protecting replants					0.198 (0.147)	0.198 (0.131)	0.330* (0.136)
EDTs						0.242. (0.133)	0.284* (0.125)
Bactericides							0.090 (0.135)

Note: Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Supplementary Table 5: Correlation between the propensity to adopt HLB management practices (Spearman's rank correlation coefficients)

	Scouting for ACP	**Treating perimeter**	**Testing**	**Protecting replants**	**EDTs**	**Bactericides**	**Barriers**
Surveying for symptoms	0.405***	0.166*	0.248**	0.067	0.212**	0.164*	0.015
Scouting for ACP		0.065	0.228**	-0.019	0.128	0.104	0.097
Treating perimeter			0.352***	0.302***	0.105	0.182*	0.225**
Testing				0.178*	0.401***	0.117	0.133
Protecting replants					0.177*	0.207*	0.238**
EDTs						0.247**	0.267**
Bactericides							0.094

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Supplementary Figure 1: Relationship between the perceived likelihood of HLB detection and four measures of distance to the closest HLB-positive tree. "Centroid" refers to the distance of the citrus-production area in the county indicated by the participant (or the average of the distance from the centroids of the production areas in the two counties indicated by the participant) to the closest HLB-positive tree. "Mean" is the mean distance of any grove recorded in the Citrus Research Board (CRB) database in the county indicated by the participant (or the mean of the means of two counties). "Minimum" is the minimum distance to an HLB-positive tree from any grove in the county/ies indicated by the participants. "Maximum" is the maximum distance to an HLB-positive tree from any grove in the county/ies indicated by the participants. Perceived vulnerability was assessed on an ordinal scale that was transformed to numeric for representation, so that *very unlikely*= 1, *unlikely*= 2, *maybe*= 3, *likely*= 4 and *very likely*= 5. Each point corresponds to the combination of answers from the 160 respondents to the survey. Points have been sized by the number of respondents who chose that combination.

Supplementary Figure 2: Probability of being *likely* or *very likely* to adopt the HLB management practices according to the explanatory factors included in the multivariate ordinal logistic regression model. The x axis shows the numeric equivalent of the ordinal ratings given to each explanatory factor (*very unlikely, unlikely, maybe, likely* and *very likely* for perceived vulnerability, staying informed and communicating with the grower liaison and communicating with neighbors; and *less than 5 acres, 5-25 acres, 26-100 acres, 101-500 acres* and *more than 500 acres* for citrus acreage). Each explanatory factor is shown in the grey box above each panel. The y axis represents the probability of being likely or very likely to adopt each practice, represented in a different color according to the legend on the right.

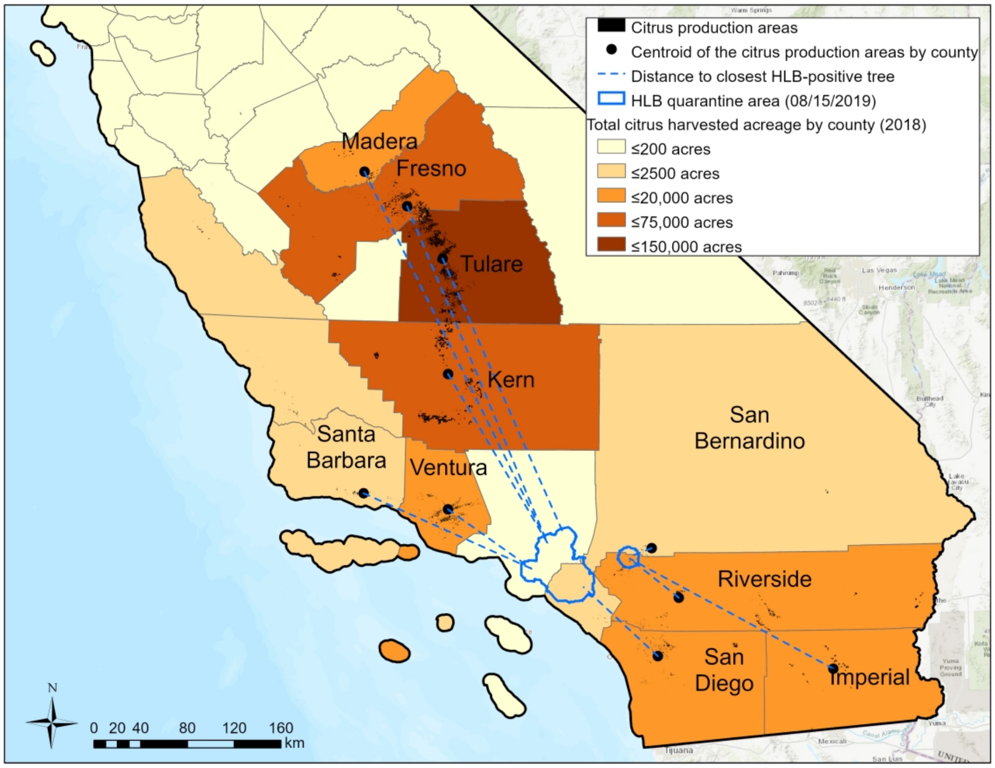

Figure 1: Distance from the centroid of the citrus acreage in each county to the closest HLB-positive tree detected by the California Department of Food and Agriculture (CDFA). The areas shaded in black represent the citrus production areas according to the Citrus Research Board (CRB) database (Rick Dunn, pers. comm.). The black dots represent the coordinates of the centroid of those citrus production areas in each county. The blue dashed lines represent the distance from the centroids to the closest HLB-positive tree (actual distances are shown in Supplementary Table 1). The coordinates of the HLB-positive trees were obtained from the Citrus Pest and Disease Prevention Program (CPDPP) database maintained by CDFA under terms of a data confidentiality memorandum of understanding between CDFA, the University of California and CRB. The perimeter of the HLB quarantine zone at the time of the survey is shown in blue (Robert Johnson, pers. comm.). The counties where survey participants had citrus groves have been labelled and colored in shades of orange according to the total citrus acreage harvested in each county in the year 2018 (Tulare CAC 2019; Riverside CAC 2019; Imperial CAC 2019; Fresno CAC 2019; Madera CAC 2019; San Bernardino CAC 2019; Kern CAC 2019; Ventura CAC 2019; Santa Barbara CAC 2019, San Diego CAC 2019).

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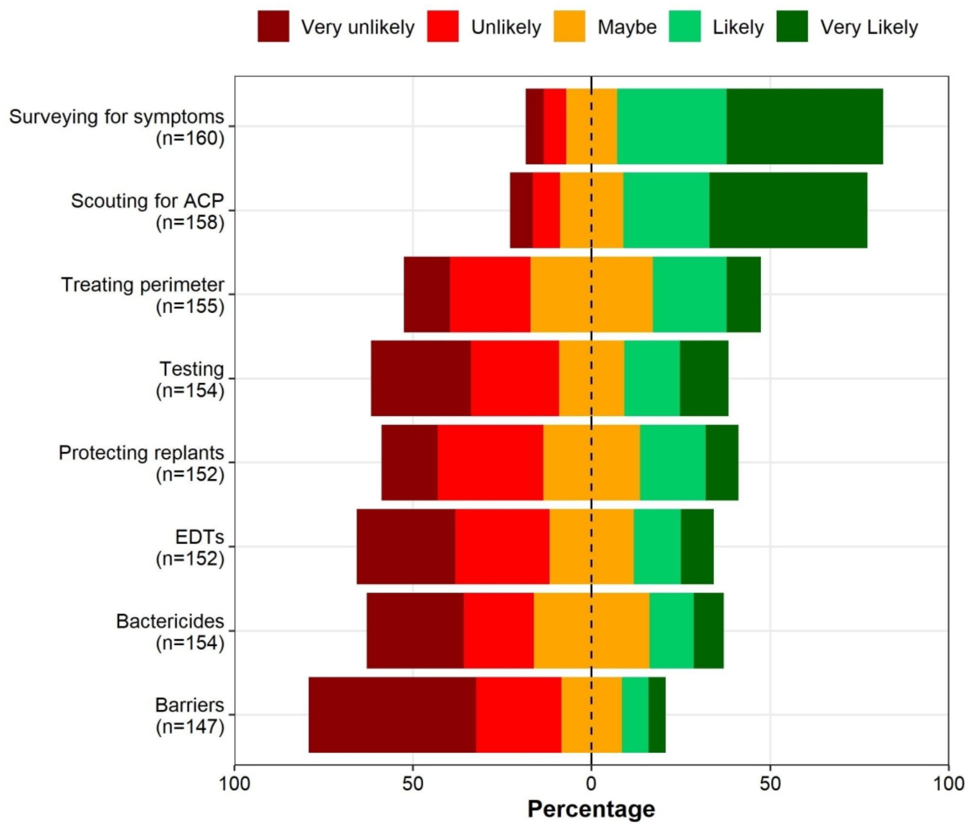

Figure 2: Reported propensity to adopt the best management practices for HLB. The practices assessed in the survey are shown on the y axis, ordered from highest (top) to lowest (bottom) percentage of likely and very likely. The percentage of responses to each question was calculated on a total number of responses indicated between parentheses under each practice. The legend at the top shows the correspondence between the response chosen and the colors on the plot.

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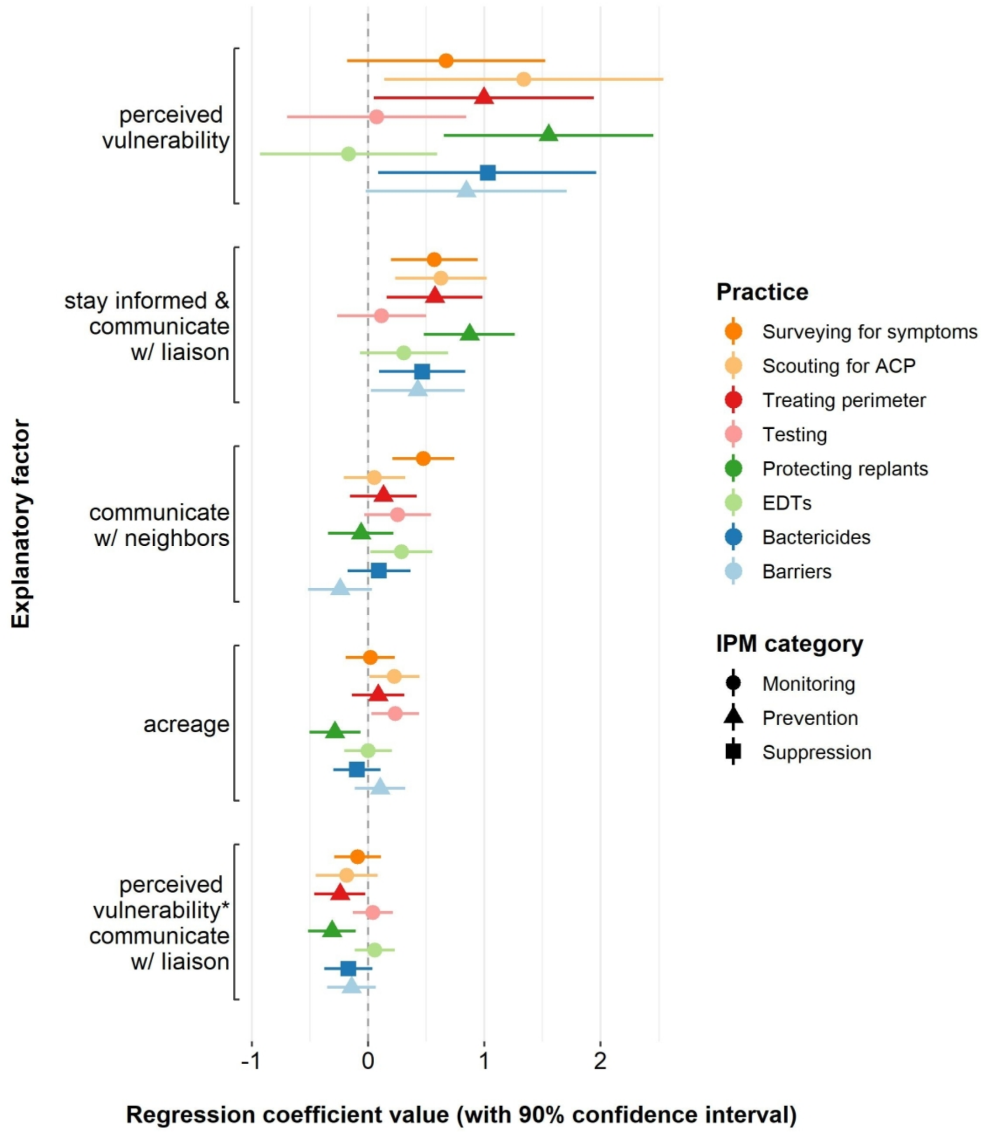

Figure 3: Confidence intervals of the regression coefficients estimated by the multivariate ordinal regression model. The x axis represents the values of the regression coefficients. The y axis identifies the explanatory factor that the coefficients correspond to. The symbols correspond to the value of the regression coefficient on each explanatory factor for each practice estimated by the multivariate ordinal regression model, and the whiskers represent the 90% confidence interval around the estimated value. The shape of the symbols represents the integrated pest management (IPM) category that each practice was classified under, and the colors represent the practice according to the legend on the right. Practices have been ordered from highest to lowest propensity to adopt (percentage of likely and very likely), according to Fig. 2.

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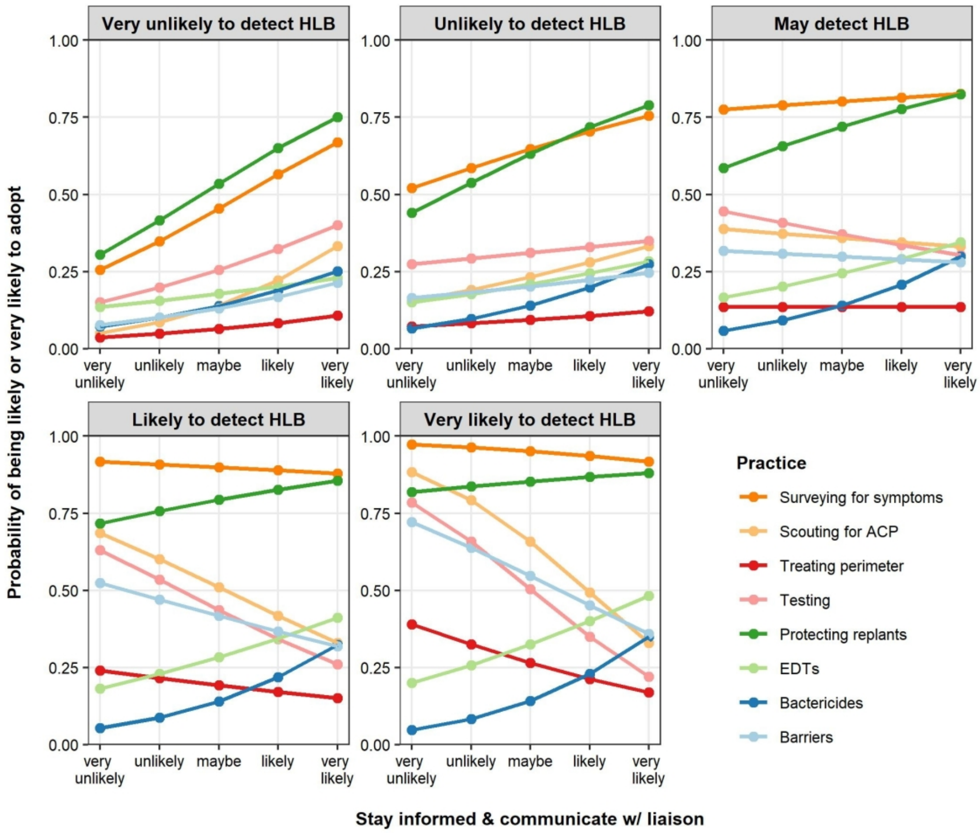

Figure 4: Probability of being likely or very likely to adopt the best management practices for HLB according to the perceived vulnerability to HLB and the propensity to stay informed and communicate with the grower liaisons. The practices were colored according to the legend on the right.

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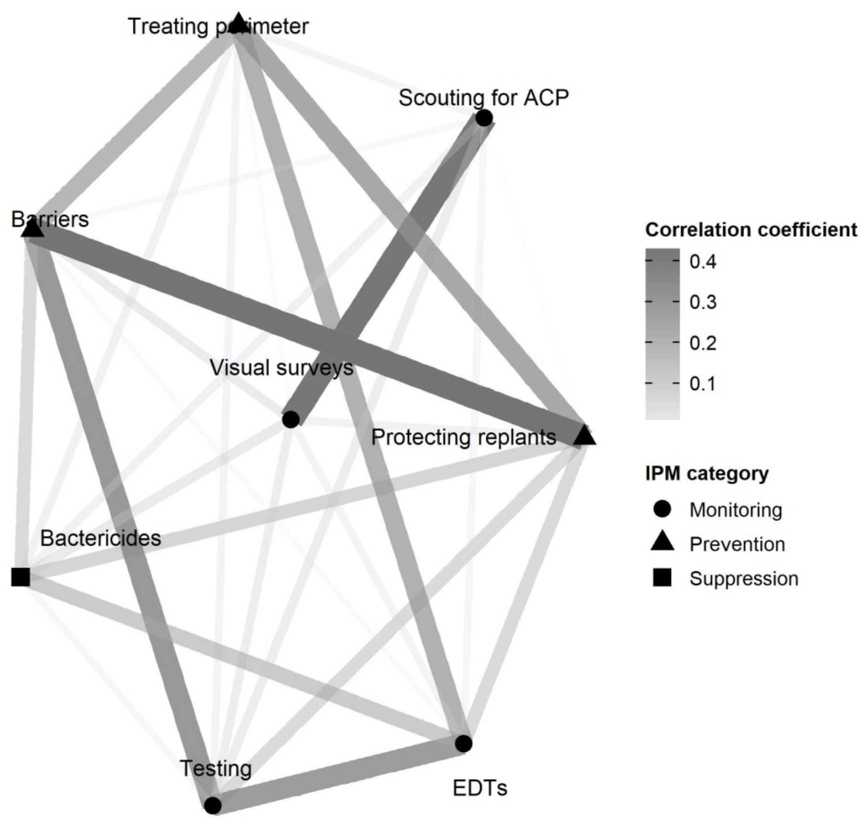

Figure 5: Interdependence in the propensity to adopt the best management practices for HLB, as estimated by the multivariate ordinal logistic regression model. The nodes in the network correspond to each practice, with different shapes for the integrated pest management (IPM) category each practice belongs to, according to the legend on the right. The width and color of the edges between nodes correspond to the correlation coefficient between practices estimated by the multivariate ordinal logistic regression model (Supplementary Table 5).

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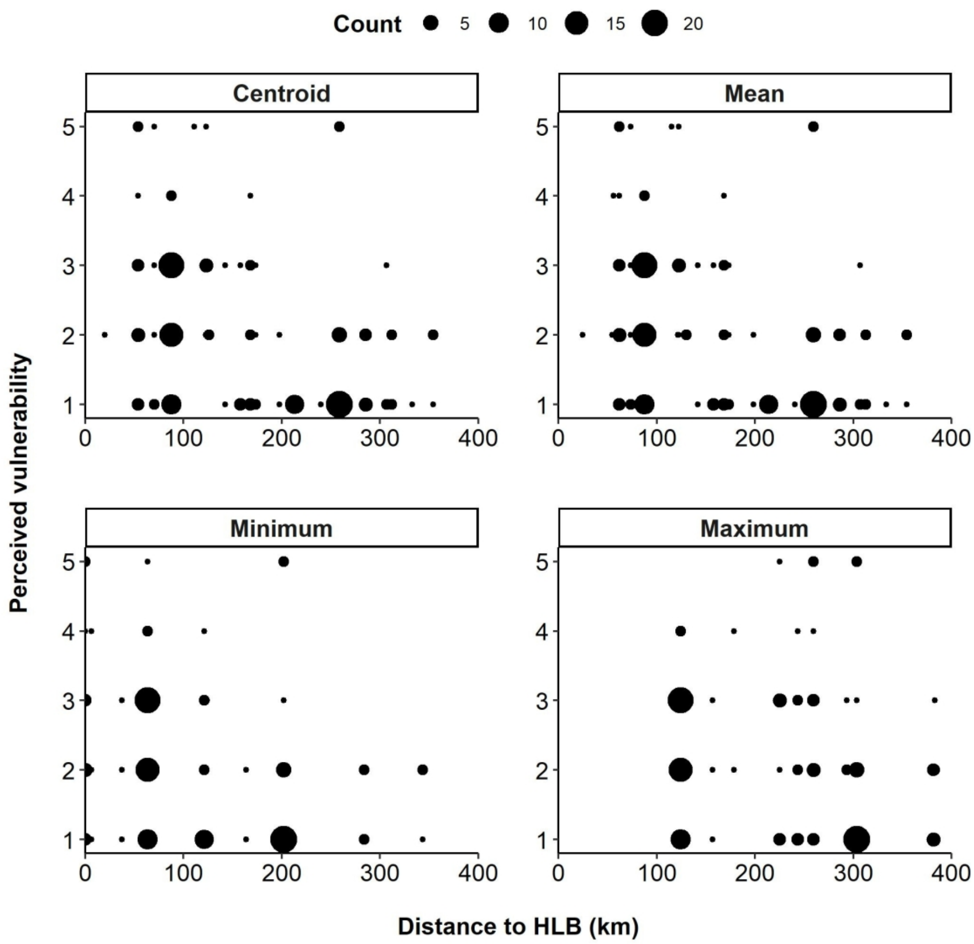

Supplementary Figure 1: Relationship between the perceived likelihood of HLB detection and four measures of distance to the closest HLB-positive tree. "Centroid" refers to the distance of the citrus-production area in the county indicated by the participant (or the average of the distance from the centroids of the production areas in the two counties indicated by the participant) to the closest HLB-positive tree. "Mean" is the mean distance of any grove recorded in the Citrus Research Board (CRB) database in the county indicated by the participant (or the mean of the means of two counties). "Minimum" is the minimum distance to an HLB-positive tree from any grove in the county/ies indicated by the participants. "Maximum" is the maximum distance to an HLB-positive tree from any grove in the county/ies indicated by the participants. Perceived vulnerability was assessed on an ordinal scale that was transformed to numeric for representation, so that very unlikely= 1, unlikely= 2, maybe= 3, likely= 4 and very likely= 5. Each point corresponds to the combination of answers from the 160 respondents to the survey. Points have been sized by the number of respondents who chose that combination.

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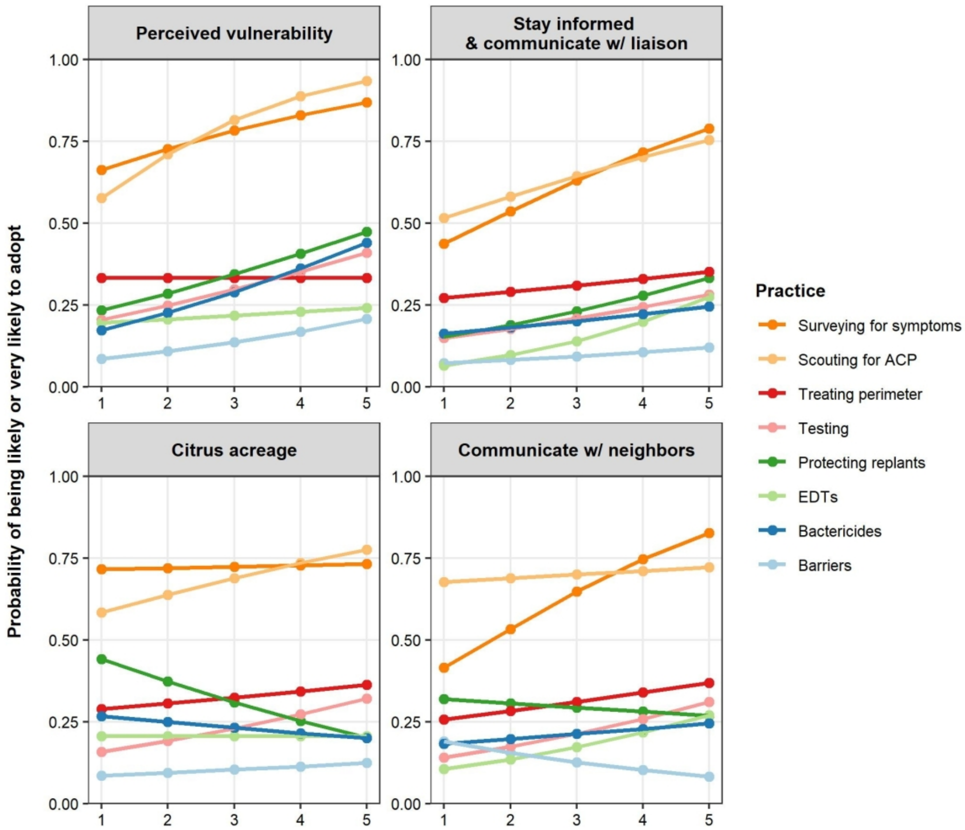

Supplementary Figure 2: Probability of being likely or very likely to adopt the HLB management practices according to the explanatory factors included in the multivariate ordinal logistic regression model. The x axis shows the numeric equivalent of the ordinal ratings given to each explanatory factor (very unlikely, unlikely, maybe, likely and very likely for perceived vulnerability, staying informed and communicating with the grower liaison and communicating with neighbors; and less than 5 acres, 5-25 acres, 26-100 acres, 101-500 acres and more than 500 acres for citrus acreage). Each explanatory factor is shown in the grey box above each panel. The y axis represents the probability of being likely or very likely to adopt each practice, represented in a different color according to the legend on the right.

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Huanglongbing Multiagency Coordination (HLB MAC)
Quarterly Progress Report

Project Title: Dynamics of Asian Citrus Psyllid under biocontrol
Cooperative Agreement Number: AP18PPQS&T00C238

Principal Investigator: Dr Neil McRoberts, UC Davis

ADODR: Dr Don Seaver

Agreement Reporting Quarter: Second

Reporting Period	*Due Dates*
Final Report	*June 1 2020*

For each project objective, please update the following information.

Project Objective: Develop demography model for ACP

Percent Completion:
Indicate percent completion of stated objective (in increments of 10)

	0	1	2	3	4	5	6	7	8	9	10	
0%	( )	( )	( )	( )	( )	( )	( )	( )	( )	()	(X)	100%

Project Milestones:

Milestone 1. We used data supplied by Dr David Hall (USDA-ARS) and from published sources to construct a series of seasonal projection matrices for reproduction, survival and demographic development (i.e. transitions among life stages from egg to adult) for Asian Citrus Psyllid. Data collation from Texas and Florida did not occur, but the modular nature of the model would allow for projection of population dynamics under conditions resembling either of these states to be completed.

Milestone 2. Four matrices were constructed, corresponding to Spring, Summer, Autumn (Fall) and Winter seasons. We assumed that reproduction and population development are possible in Spring and Fall, but not in Summer or Winter. This pattern matches the periods when oranges and mandarins produce their main flush under California conditions. The model is a stylized version of reality that exaggerates observed trends in population dynamics and structure in Southern California. Survival over Summer and Winter in the model is in the form of adults only. Each "season" is assumed to be 90 days in duration and the four matrices are assumed to project the population forward on a daily time step.

The effects of parasitism by *Tamarixia radiata* were included in the model by altering the survival probabilities for stage 4 and 5 instars, in line with observed parasitism rates for these life stages under natural conditions in Southern California. The overall effect of *T.radiata* on nymph survival is assumed to be a mixture of parasitism and adult feeding, with the ratio of mortality induced by the two effects assumed to be 3:1 parasitism to adult feeding.

All four life-stage matrices have the same structure, comprising 7 living stages in the ACP life-cycle – egg, 5 instars, and adults – and *dead*. The inclusion of *dead* as a life stage in the projection matrix simplifies bookkeeping in the numerical projections and allows for simple comparisons among projections with different assumed parasitism rates, or differences in life history parameters. On the other hand, because dead is an absorbing state[1] in the model the overall number of individuals in the projected populations never decreases, and some (simple) additional steps are needed in calculating population sizes for comparison purposes. The generic life cycle model for each season is shown in Figure 1; the corresponding projection matrices have the general form:

$$\begin{pmatrix} p_{1,1} & 0 & 0 & 0 & 0 & 0 & f_1 & 0 \\ p_{2,1} & p_{2,2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p_{2,3} & p_{3,3} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & p_{4,3} & p_{4,4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{5,4} & p_{5,5} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{6,5} & p_{6,6} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{7,6} & p_{7,7} & 0 \\ p_{8,1} & p_{8,2} & p_{8,3} & p_{8,4} & p_{8,5} & p_{8,6} & p_{8,7} & p_{8,8} \end{pmatrix} \tag{1}$$

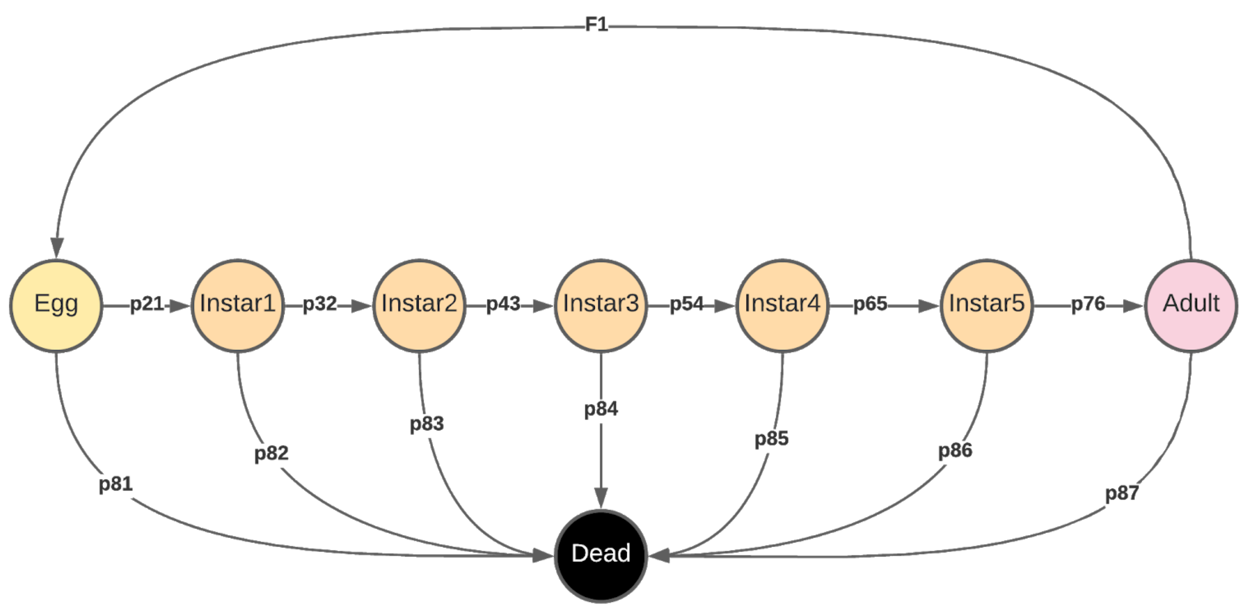

Figure 1. *Basic life cycle model for ACP corresponding to the generic projection matrix shown in equation 1. Projection for each season is based on the same structure but the values of transition probabilities between stages and the fecundity change. When present, T.radiata affects the transitions from Instar 4 to Instar 5 and from Instar 5 to Adult, by killing a proportion of Instars 4 and 5.*

Figure 2 shows the outcome of projecting the baseline set of life history parameters for ACP over the model year in the absence of *T.radiata*. The projection is seeded with a single adult psyllid on day 1, so that the ratio of the final to initial adult population sizes gives an estimate of the annual, uncontrolled, population growth rate.

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[1] An absorbing state is one for which there is a path in from other parts of the life cycle but no exit path; when included explicitly in a life history model, death is always an absorbing state.

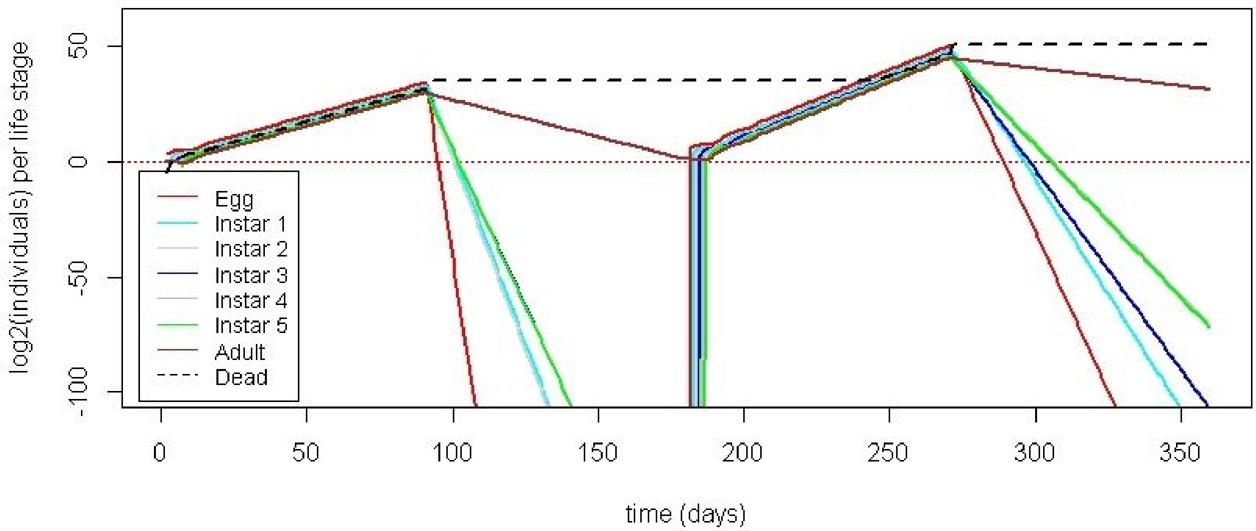

Figure 2. *Projected population dynamics for the Asiam Citrus Psyllid in the absence of control over s stylized year consisting of 4 seasons of 90 days each. The year begins with Spring and follows the natural sequence of seasons. Reproduction is possible in Spring and Fall. In Summer and Winter non-adult life stages have high mortality and no possibility for development and effectively reach zero population size within the season. Adults survive but with a fixed daily probability of death. Mortality rates are assumed to be higher in Summer than Winter. Note the vertical axis is on a log_2 scale so the horizontal reference line at 0 corresponds to a single individual.*

The annual growth rate under the baseline assumptions and no biocontrol was calculated to be 2.68e+09 (2.7 trillion). The daily growth rate in the Spring and Fall seasons was, respectively, 1.28 and 1.43. The baseline life stage parameters, by season, are shown Figure 3.

For the Spring period of population growth, the baseline projection model had a stable stage distribution in which 55% of the ACP population was in the form of eggs, the remaining 45% being split among the other 6 life stages. Adults accounted for 3% of the population, 4^{th} and 5^{th} instars 5% and 4% each, respectively.

In contrast to the stable stage distribution, the reproductive value of specific stages increased from egg to adult. With the reproductive value for eggs set to 1.00, the values for 4^{th} and 5^{th} instars were 8.18 and 13.94, and that for adults was 35.21; adult ACP, in spite of comprising only 3% of the population had between 2 and 3 times the value of the next most valuable state and 35 times the value of eggs.

These same patterns of stage distribution and reproductive value were repeated in the Fall projection model, but with the values being more pronounced; 61% of individuals were eggs, only 1.4% were adults with 4^{th} and 5^{th} instars comprising 4% and 2%. Adults had a reproductive value 68 times higher than that of eggs, while the values for 4th and 5th instars were 13.50 and 27.23 times higher than that for eggs.

Spring

$$\begin{pmatrix} 0.76 & 0 & 0 & 0 & 0 & 0 & 11.43 & 0 \\ 0.24 & 0.48 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.50 & 0.36 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.62 & 0.40 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.59 & 0.57 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.42 & 0.79 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.19 & 0.95 & 0 \\ 0.04 & 0.02 & 0.02 & 0.01 & 0.01 & 0.01 & 0.04 & 1.00 \end{pmatrix}$$

Summer

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.10 & 0.10 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.15 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.15 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.15 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.8 & 0 \\ 0.9 & 0.90 & 0.90 & 0.85 & 0.85 & 0.85 & 0.20 & 1.00 \end{pmatrix}$$

Fall

$$\begin{pmatrix} 0.68 & 0 & 0 & 0 & 0 & 0 & 31.30 & 0 \\ 0.29 & 0.36 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.62 & 0.27 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.71 & 0.46 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.53 & 0.55 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.43 & 0.69 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.29 & 0.97 & 0 \\ 0.03 & 0.02 & 0.02 & 0.01 & 0.01 & 0.01 & 0.03 & 1.00 \end{pmatrix}$$

Winter

$$\begin{pmatrix} 0.15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.10 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.30 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.30 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.40 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.40 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.90 & 0 \\ 0.75 & 0.75 & 0.70 & 0.70 & 0.60 & 0.60 & 0.10 & 1.00 \end{pmatrix}$$

Figure 3. *Life history parameters used in the baseline projection of the Asian Citrus Psyllid annual life cycle with no biocontrol. The sequence of life stages in the matrix rows and columns follows the sequence shown in figure 2. Eggs are the first row/column, death is the final row/column. Presence of T.radiata affects the probabilities in columns 5 and 6. Values shown are daily numbers.*

Milestone 4

With the baseline model established, we added the effect of biocontrol by *T.radiata* by running a series of projections with increasing levels of mortality induced in the 4th and 5th instars by the parasitoid. The range of values used reflects the range of parasitism estimates reported from the California *T.radiata* release Task Force, with values ranging from 5% to 80%. The results of these projections are summarized in Figure 4, which shows the response of ACP population annual growth rate to parasitism. We found that the projection model indicated that ACP population growth was stopped when parasitism rates in both Spring and Fall were in the order of 33% per day. Given the uncertainty about the numerical accuracy of some of the estimated parameters in the projection model and the fact that it does not contain any stochasticity, it is not advisable to place too much emphasis on the numerical result here, but it ***is*** an important qualitative result that the projection model includes, within its output range, parasitism-induced population control.

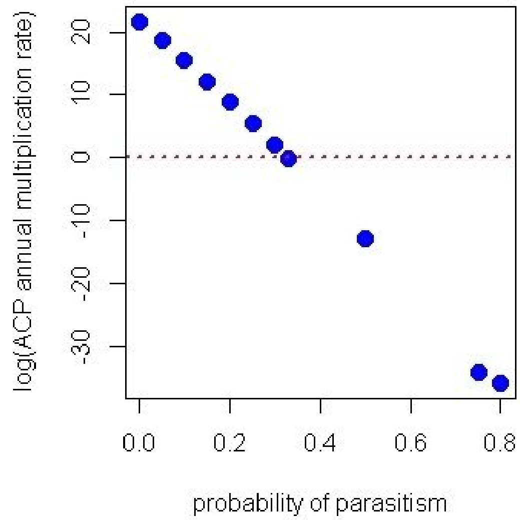

Figure 4. *The projected response of ACP population annual growth to increasing probability of parasitism at an individual scale. Population growth is projected to stop (log growth rate = 0 indicated by the horizontal dotted line) when the probability of parasitism reaches 0.33.*

Figure 5 shows the projected annual population dynamics with the probability of parasitism set at 0.33 (*i.e.* the value at which ACP population growth stops). Comparison of Figure 5 with Figure 2 gives a direct evaluation of the impact on population growth from the assumed level of parasitism.

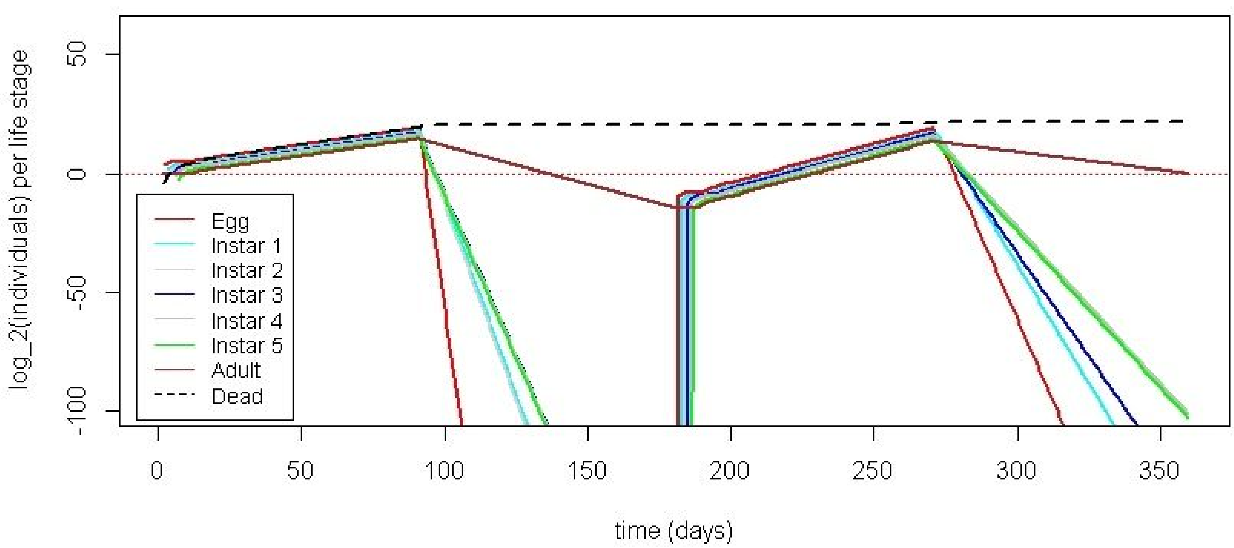

Figure 5. *ACP population growth is static in the projection model at a parasitism rate probability of 0.33.*

It is worth emphasizing that maintaining a daily probability of parasitism of 0.33 in real life is difficult. The key result from this analysis is probably not the numerical estimate of the value at which idealized parasitism would push the ACP population to zero growth, but more the qualitative result that parasitism may be able to impact ACP population growth at all. This is important because it indicates that, based on rather mild assumptions that combine life history parameters estimated from controlled environment studies, and a simplified view of the impact of environment on ACP reproduction in a Mediterranean climate, biocontrol through stage-specific parasitism may have a useful impact on ACP population growth.

Project Objective: Time series analysis of ACP population data

Percent Completion:

Indicate percent completion of stated objective (in increments of 10)

	0	1	2	3	4	5	6	7	8	9	10	
0%	( )	( )	( )	( )	( )	(X)	( )	( )	( )	(X)	()	100%

Project Milestones:

Milestone 1: We collected ACP population data from the CHMA program in FL and the CPDPC survey program in CA. These data are surveys carried out for monitoring purposes and not from manipulative experiments so the ACP dynamics present in the datasets reflect the full, unrestricted set of forces acting on the ACP population in each of those environments, including natural predation, parasitism from released *T.radiata*, and pest management activities. The data from CA comprise presence/absence (incidence) observations for traps placed in a stratified sample of commercial citrus (predominantly) across Southern California. For FL, the data consist of ACP counts for large numbers of tap samples collected during the regular statewide survey of commercial citrus. Since the data for CA are bounded in the range [0,1] we transformed the FL data by dividing by the maximum value of each series to transform them to a 0 to 1 scale. The data for CA consisted of 60 consecutive monthly observations, the CHMA data consisted of 117 observations. We selected 3 CHMAs for comparison with CA on the basis that they represented situations in which (in the sample of data) there were varying overall ACP population sizes. Corkscrew CHMA represents an example where ACP populations were mostly low, St Lucie is an example of a CHMA with moderate to high ACP numbers, while Seminole is an example of a CHMA with initially low ACP populations that have increased to high levels in more recent surveys.

The literature search/gathering process mentioned under this milestone was not conducted.

Milestone 2: Autoregressive Statistical Models We analyzed the data mentioned under Milestone 1 to characterize ACP population dynamics in southern California and Florida. The process of time series diagnostics uses a set of techniques selected to characterize the time series in terms of their tendency to stochastic noise versus deterministic chaos, and extract the best-fitting simple auto-regressive model for the logarithmic rate of change along the series. Some of the diagnostic methods are based on assumptions of stationarity in the series, so the data were first inspected for trend and where necessary, a linear regression was used to remove the trend before further analysis.

Figure 6 shows the detrended series for the California locations – Riverside, San Bernardino, and Ventura – and the three Florida CHMAs – Corkscrew, Seminole, and St Lucie.

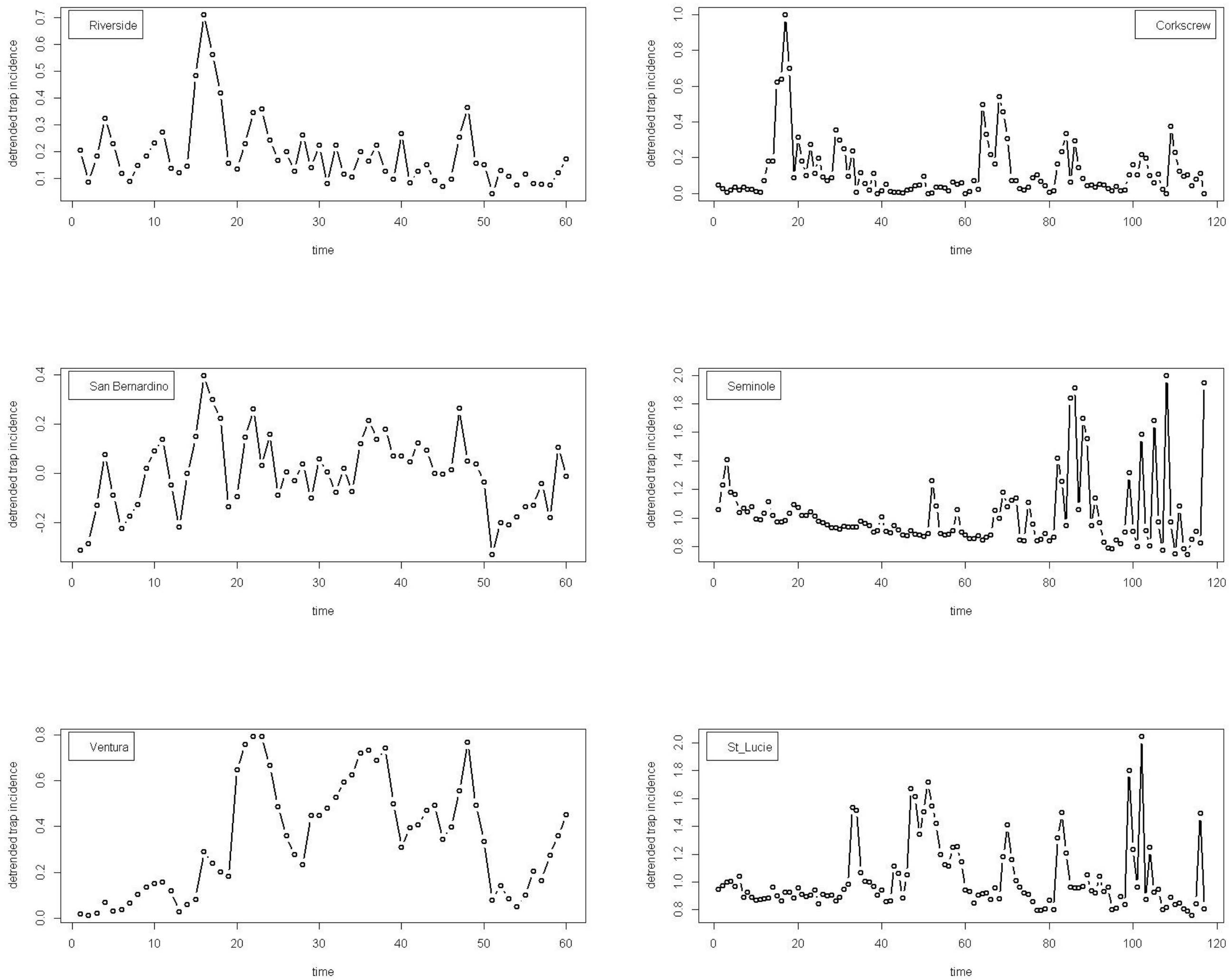

Figure 6. *Detrended time series data for Asian Citrus Psyllid populations in three California counties (left column) and three Florida CHMAs. The raw data were in the form of incidence (0 to 1 scale). Note that the Florida data series have almost twice as many data points as the California data series so visual comparison of the frequency of peaks may be misleading in relation to population dynamic*s.

Figure 7 presents the time series data in the form of phase plots in which the value of the series at time t+1 is plotted on the vertical, against the value of the series at time t. In this format, if a population series is under regulation it will appear to orbit a point in the coordinate space in (perhaps irregular) clockwise orbits.

We used two methods to assess the extent which the series tend toward stochastic or chaotic (deterministic) uncertainty. First, we calculated the dominant Lyapunov Exponent for each series. For series that have chaotic dynamics the Lyapunov Exponent is positive, indicating that randomly selected trajectories produced by the data-generating process will diverge over time (although if they are truly chaotic their oscillations will be bounded within limits); a negative value indicates series that are dominated by stochastic noise and will tend to converge in the limit. We also used a data resampling (surrogate) test which is based on the idea that a pure linear stochastic process is time-reversible.

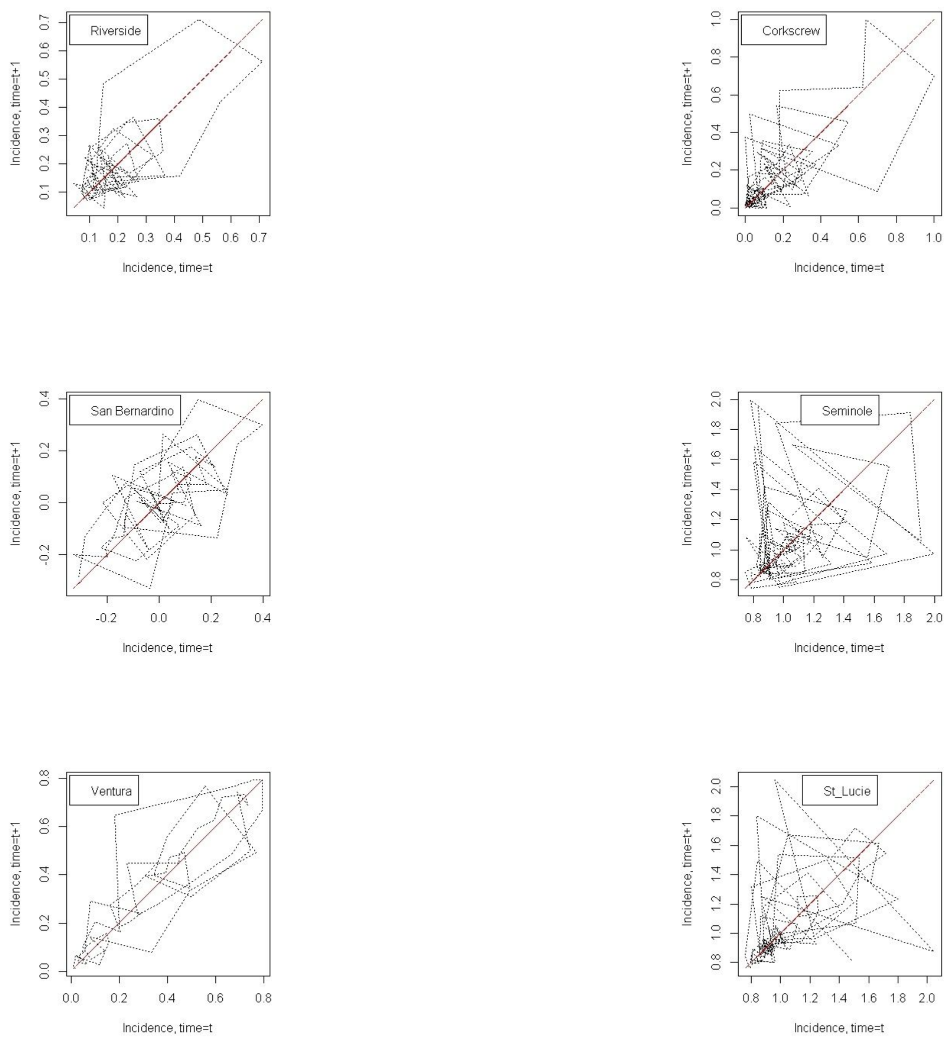

Figure 7. *Phase plots for Asian Citrus Psyllid population time series from California (left column) and Florida (right column) locations. The plots show the population size value at time t+1 on the vertical plotted against its value at time t for each successive t,t+1 pair along the series. Note that the California series tend to form orbits that lie close to the diagonal on which t+1 = t, whereas the Florida datasets, particularly Seminole and St Lucie occupy a larger area within the parameter space and include sections in their trajectories that cross the diagonal more or less perpendicular to its orientation.*

The basic idea of this test is to construct a large number of resampled versions of the original data that are constructed in such a way as to guarantee time-reversibility. A test statistic that is sensitive to failure of time reversibility is calculated for the original data and the resamples. If the test statistic lies in the upper or lower tail of the distribution of samples, the null hypothesis of linear stochasticity is rejected. Table 1 summarizes the outcome of the two types of test. Figure 8 shows the distributions of the test statistics for each of the time-series.

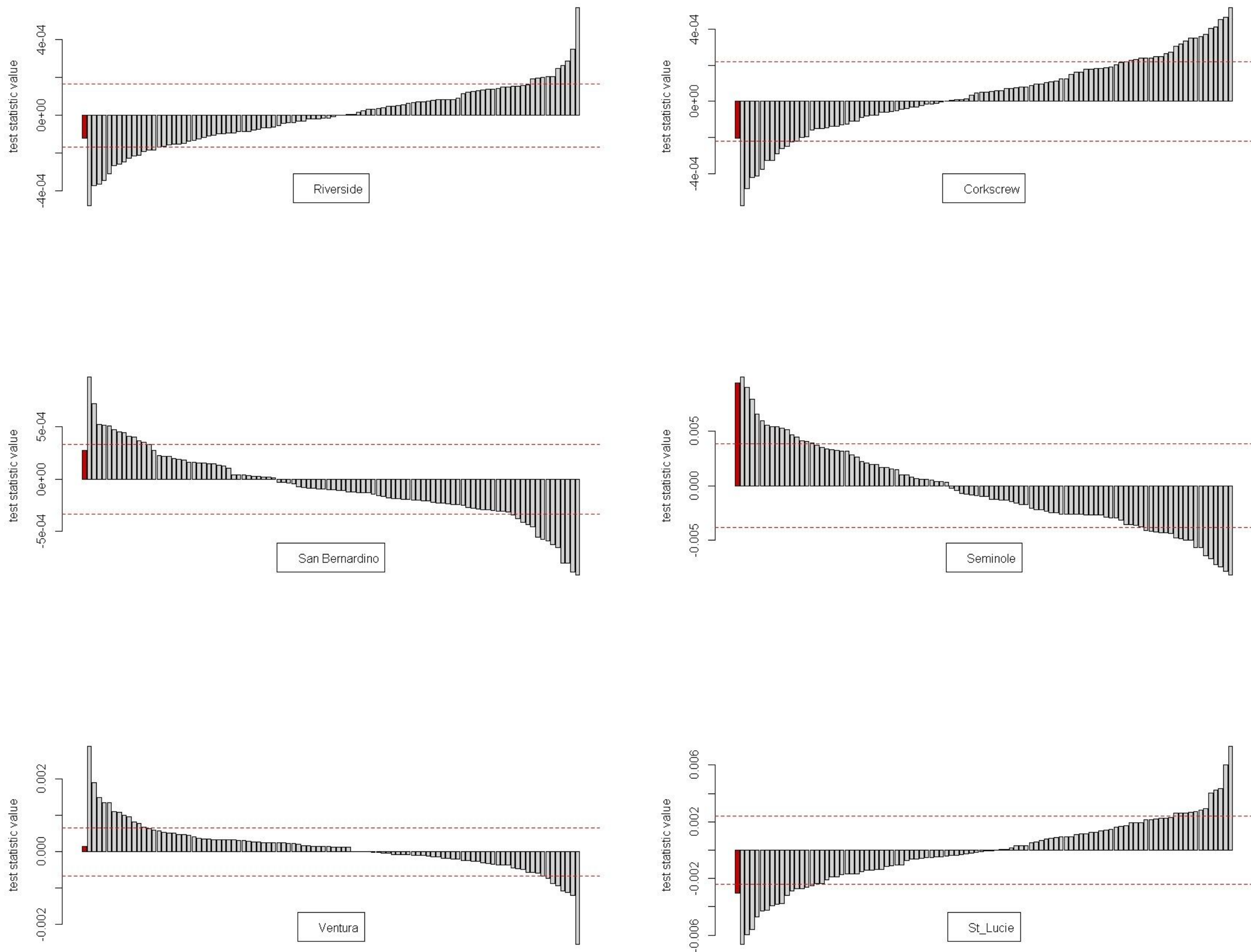

Figure 8. *Surrogate test statistic distributions for a time-reversibility test of Asian Citrus Psyllid population time series from six locations. In all plots the left-most, red, bar shows the value of the actual data series, the gray bars are values for 99 resampled data sets based on the original data. The null hypothesis is that the original data are generated by a linear stochastic process (and will therefore show reversibility). The test is a two-way test with an empirical limit of p=0.02. The red dashed lines show the standard deviation of the resampled data. The test fails to reject the null hypothesis in all cases, but not the relative magnitude of the test statistic in the cases of Seminole and St. Lucie.*

Overall, the results indicated that time series data from all six locations had properties of both stochastic and chaotic processes and were, probably, in the transition zone from one type of dynamics to the other. This “mixed” or quasi-chaotic behavior is not unusual in biological time series. The data from the three Florida locations were slightly more consistent in their dynamic properties, inasmuch as all three had positive Lyapunov exponent values (indicating a tendency to chaos) but also failed to reject the test for linear stochasticity. In contrast, two of the three California locations had negative

Lyapunov exponents (indicating stochastic noise) and one had a positive value. As with the Florida

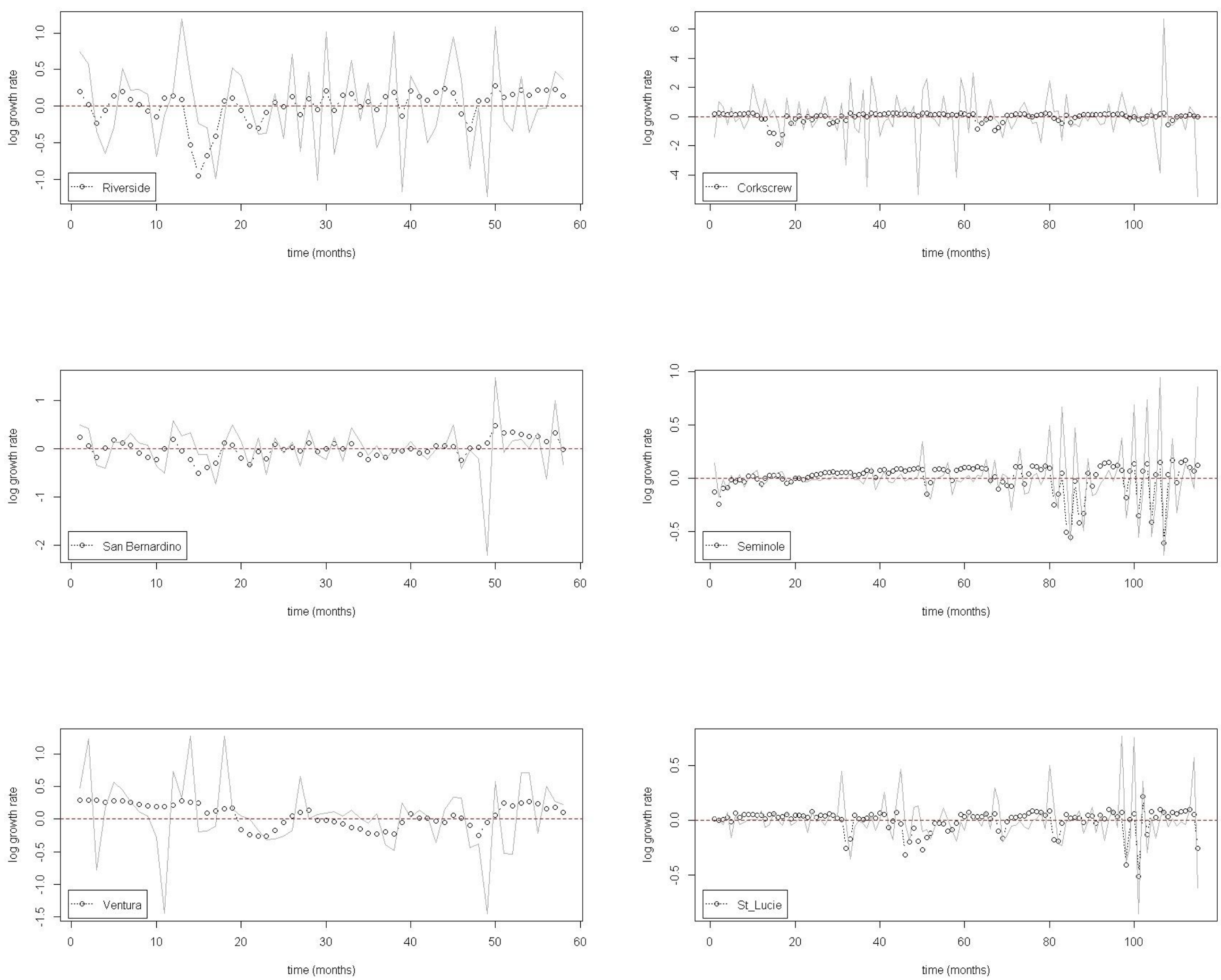

Figure 9. *Time series for instantaneous log growth rate for Asian Citrus Psyllid in six locations in California and Florida, with fitted values for autoregressive models. The data are shown as solid grey lines, the fitted models are shown as open circles connected by dashed lines. The horizontal dashed red line indicates the value for a stable population size.*

data, all three California locations failed to reject the null hypothesis of linear stochasticity. Investigation of further time series properties through studying the autocorrelation structure and the more general measure of association provided by the average mutual information function, showed that all six series were likely to have relatively simple autocorrelation models, although the structural analysis does not predict how good the best fitting model will be.

Table1. *Estimated Lyapunov exponent values and surrogate test outcomes for 6 Asian citrus Psyllid population time series.*

Location	Lyapunov Exponent	Surrogate test outcome
Riverside	-0.022 (stochastic)	linear, stochastic
San Bernardino	0.065 (chaotic, deterministic)	linear stochastic
Ventura	-0.036 (stochastic)	linear, stochastic
Corkscrew	0.256 (chaotic, deterministic)	linear, stochastic
Seminole	0.050 (chaotic, deterministic)	linear, stochastic
St Lucie	0.041 (chaotic, deterministic)	linear, stochastic

Milestone 3. Simulation model. Based on the regression analysis, and bearing in mind results from the literature we opted for a relatively simple approach to construct mathematical models for the interaction between ACP and the parasitoid *T.radiata*. The aim is to provide a simple but flexible platform that can be used in combination with the other numerical tools we have developed to analyze the data from biocontrol efforts from any location. The basic model is shown in equation set 1 in which N_t is the ACP population and P_t is the parasitoid population.

$$\begin{aligned} N_{t+1} &= N_t \cdot exp\left[r\left(1 - \frac{N_t}{k}\right) - \frac{aP_t}{1+ahN_t} \right] \\ P_{t+1} &= N_t \cdot \left[1 - exp\left(- \frac{aP_t}{1+ahN_t} \right) \right] \end{aligned} \tag{1}$$

The pair of difference equations models the density-dependent ACP population growth as a logistic process (the first set of terms inside the exponential in the first equation) and parasitoid functional response as a rectangular hyperbolic function (also called a type II functional response in the population ecology literature). The parameters are: r, the ACP growth constant, k, the limiting ACP population size; a the parasitoid attack rate and h, the host handling time.

Using parameter values for ACP selected to produce density dependent approach to maximum population size in 90 days and parameter values for the parasitoid selected from those found by Phil Stansely and colleagues in controlled environment studies results in the dynamics shown in Figure 10.

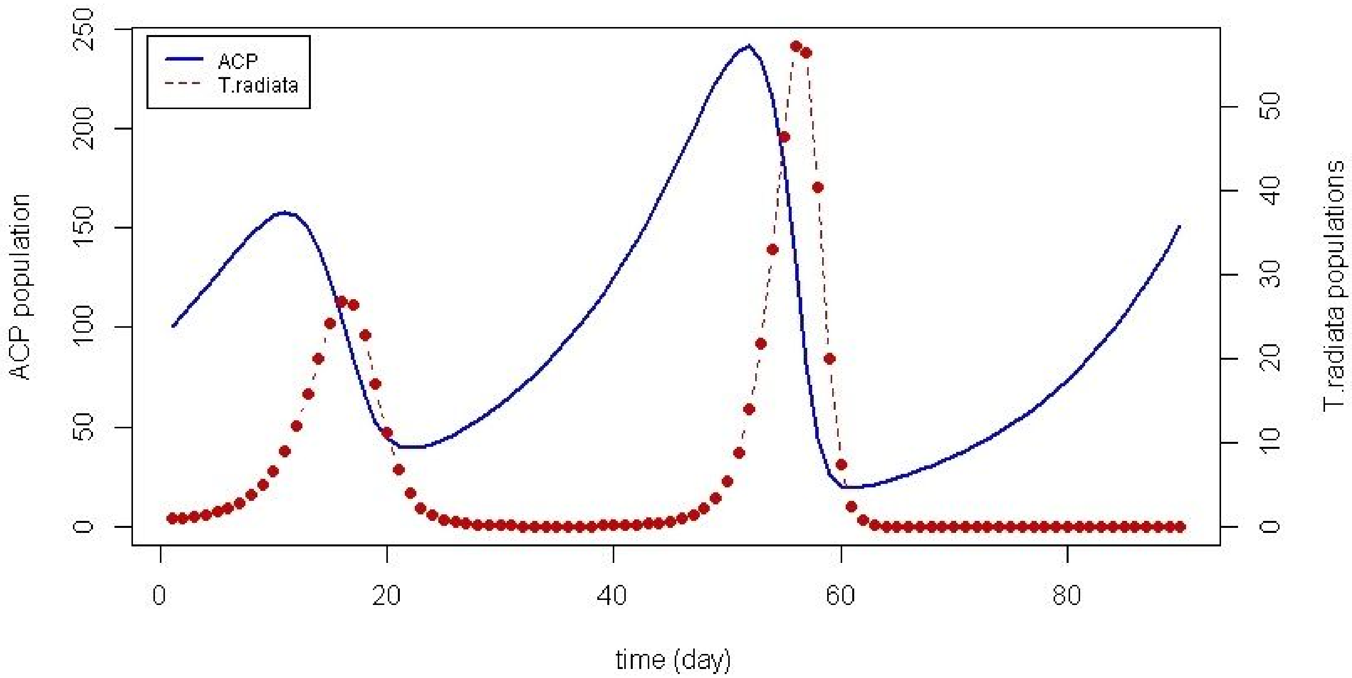

Figure 10. Illustration of the dynamics of the selected host-parasitoid model for ACP and T.radiata. Parameter values for this output were r = 0.075, k = 2500, a=0.02, h=0.4. The initial ACP population size was 100 and the initial *T.radiata* population was 1.

Obstacles:

There are no obstacles to report at this time.

Tangible Benefits:

The project has generated a set of numerical tools which can be used to support on-going work on the evaluation and deployment of *T.radiata* for biocontrol of ACP. We intend to integrate these tools into our wider evaluation of program activities in California and also to offer support to colleagues from Florida or Texas who may want to make use of the resources for their own analyses. We will incorporate these activities into existing work supported by the MAC program, the Citrus Research Board and UC ANR.

Outreach and Communication:

Given the sensitivity of the subject of biocontrol we have not made any effort to convey the results of our work to colleagues or stakeholders. With the conclusion of the project, and our intention to move the work into our routine activities, we will contact the California biocontrol Task Force and make them aware of our findings.

PHILOSOPHICAL TRANSACTIONS B

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Review

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Author for correspondence:
Neil McRoberts
e-mail: nmcroberts@ucdavis.edu

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Using models to provide rapid programme support for California's efforts to suppress Huanglongbing disease of citrus

Neil McRoberts[1], Sara Garcia Figuera[1], Sandra Olkowski[1], Brianna McGuire[1], Weiqi Luo[2,3], Drew Posny[2,3] and Tim Gottwald[2]

[1]Plant Pathology, University of California, Davis, CA 95616, USA
[2]U.S. Department of Agriculture, Agricultural Research Service, Fort Pierce, FL 34945, USA
[3]Center for Integrated Pest Management, North Carolina State University, Raleigh, NC 27695, USA

NM, 0000-0001-6346-9461; TG, 0000-0003-0885-8004

We describe a series of operational questions posed during the state-wide response in California to the arrival of the invasive citrus disease Huanglongbing. The response is coordinated by an elected committee from the citrus industry and operates in collaboration with the California Department of Food and Agriculture, which gives it regulatory authority to enforce the removal of infected trees. The paper reviews how surveillance for disease and resource allocation between detection and delimitation have been addressed, based on epidemiological principles. In addition, we describe how epidemiological analyses have been used to support rule-making to enact costly but beneficial regulations and we highlight two recurring themes in the programme support work: (i) data are often insufficient for quantitative analyses of questions and (ii) modellers and decision-makers alike may be forced to accept the need to make decisions on the basis of simple or incomplete analyses that are subject to considerable uncertainty.

This article is part of the theme issue 'Modelling infectious disease outbreaks in humans, animals and plants: epidemic forecasting and control'. This theme issue is linked with the earlier issue 'Modelling infectious disease outbreaks in humans, animals and plants: approaches and important themes'.

1. Introduction

California, which has approximately 109 000 Ha (268 000 acres) of commercial citrus, is the most recent citrus-growing region to be threatened by Huanglongbing (HLB) [1,2]. HLB is associated with a non-reversible decline in tree vigour and fruit yield. Yield loss results from: reduced fruit number, size and mass; early fruit drop; failure to ripen; and unmarketable flavour. Citrus trees of all commercial species and varieties are susceptible and typically die less than 10 years after symptoms first become apparent.

HLB is associated with the Gram-negative fastidious bacteria *Candidatus* Liberibacter spp. which are vectored by two species of psyllids: the Asian citrus psyllid (ACP), *Diaphorina citri*, and the African citrus psyllid, *Trioza erytreae*. Of the two, ACP is of greater global concern and is the exclusive vector present in North, South and Central America, where it has spread '*Candidatus* Liberibacter asiaticus' (CLas) in most key citrus-growing areas.

In California, ACP was first detected in 2008 and CLas in 2012. A coordinated response to suppress ACP populations and limit the spread of HLB has been in place since shortly after ACP was first detected. The Citrus Pest and Disease Prevention Committee (CPDPC) was created in 2009, when the state legislature passed the purpose-written California Agriculture Bill AB-281, requiring the State Secretary of Food and Agriculture to establish a grower-funded programme for citrus pest and disease control, the California Citrus Pest and Disease Prevention Program (CPDPP). The CPDPC consists of 17 voting members (14 growers, two nursery tree producers and one public member), who make recommendations to the California Department of Food and Agriculture (CDFA) for the implementation of the CPDPP. Thus, the CPDPP operates under the regulatory jurisdiction of the CDFA. If a tree is confirmed by the approved regulatory diagnostic protocol—a quantitative polymerase chain reaction (qPCR)—to have CLas DNA present in its tissues, it must be destroyed. If tree owners in any context refuse to allow a qPCR-confirmed tree to be removed, CDFA staff have the legal authority to enforce removal and recover the costs from the owner; the cost of removing voluntarily surrendered infected trees is borne by the programme.

The CPDPC has relied, since its inception, on epidemiological modelling and analysis to support decision-making and to optimize resource allocation among different programme activities, but the scope of these analyses and their integration into the decision-making process have increased over time. The aim of this paper is to give an overview of the process of integration. Rather than focus on mathematical and statistical details, we provide an illustrative description of the practical use of epidemiological modelling to address a series of questions arising in sequence during the emerging HLB epidemic. We summarize the approach taken to address each question and the outcome in terms of the activity of the programme. Consequently, the paper consists of a series of vignettes, which are intended to have pedagogical value to researchers and decision-makers who might be faced with similar challenges in other contexts. Supplementary online material is used to provide details of analyses that cannot be accommodated within the main text of the paper.

In the order in which they appear, the examples we discuss can be considered under three headings. First, we discuss issues connected with disease surveillance and detection and the allocation of resources to that important task. Second, with a successful detection programme comes the issue of handling an increasing number of potentially exposed, but not yet confirmed, cases, and how modelling can be used to explore the adoption of alternative regulatory approaches, not based on confirmation. Finally, we discuss an example of the use of participatory risk modelling in which stakeholders have been asked to assist in evaluating the risk of inadvertent disease spread associated with transport of fruit for processing and packing.

2. Disease surveillance: finding the enemy

Surveillance for vector-borne diseases presents challenges over and above those of other infectious diseases because both vector populations and disease incidence must be monitored, with a sometimes uncertain relationship between the two, as observed in the dengue fever disease system [3,4]. Once vector populations are established in an area, early detection of disease becomes the critical factor in surveillance success; where 'success' can be evaluated, in part, as the ability of a surveillance system to detect unexpected increases in disease incidence with sufficient lead-time and spatial precision to guide targeted interventions [5,6].

There are several critical challenges to achieving this goal in the context of HLB. Surveillance efficiency is limited both by sampling errors associated with the localized nature of infections in tree canopies and by the relatively long and variable intrinsic incubation period, which greatly exceeds the latent period, and gives rise to asymptomatic infections that contribute to the spread of the pathogen [2], a phenomenon that has been described in both human and veterinary vector-borne disease systems [7,8]. The resulting diagnostic errors may cause erratic identification of individual infections and thus unreliable population-level estimates of disease. A related issue occurs when closely related pathogens cause bioassay cross-reactivity [9].

Understandably enough, decision-makers become unwilling to commit resources on the basis of information that is known to be error-prone. This tension between the reliability and accuracy of disease detection, and the need for action nevertheless, has been a significant factor in the activities of the CPDPC, and a common theme running through this review is that 'Even when data are fluid, a decision must be made' [10]. In a regulatory setting, the aim is often to provide a 'good enough' basis for decision-making in real time; gathering the information for complete understanding of the dynamics is a longer-term, academic pursuit, albeit a useful one, in future decision-making.

With these challenges in mind, biological and operational factors should be considered when designing a fit-for-purpose surveillance strategy. Risk-based surveillance is a strategy that has been employed in diverse disease systems [11–13] to guide monitoring and control efforts and was the approach selected, soon after the inception of the CPDPP, to enable the programme to find and remove *C*Las-infected trees in California.

3. The primary surveillance tool: risk-based surveys for Asian citrus psyllid and Huanglongbing in California

The most important issue facing the CPDPC at the outset of the epidemic, and in continuing efforts to suppress HLB, has been to maximize the early detection of infected hosts and vectors across the state. The design of a suitable survey-sampling protocol was therefore the first analytical task faced by epidemiologists. Previous experience with HLB epidemics in China, Brazil and Florida, and knowledge of the local circumstances of citrus production in California, resulted in a risk-based survey (RBS) previously implemented in Florida being adapted for use in California as well as Texas and Arizona [14,15].

The risk model is, in effect, the summation of a series of individual risk factors to generate HLB/ACP risk scores for each relevant US section-township-range (STR) grid (i.e. 1 mile^2). The risk factors comprise a mixture of social, biophysical and environmental variables influencing HLB/ACP introduction and development within a landscape. Model components include human-mediated introduction risk from international travel, detected ACP density, Clas+ detections (trees and ACP), citrus nurseries, home improvement stores or other garden centres (which may serve as potential inoculum reservoirs), citrus transportation corridors, citrus packing houses, farmers' markets, military bases and Native-American reservations (both of which are associated with lowered levels of census data), and weather suitability for ACP and HLB development. These factors were identified, via an informal Bayesian approach using an accumulation of scientific literature and expert knowledge about the epidemiology of HLB/ACP, as well as particulars of the local situation in California (see electronic supplementary material, figure S1) to generate risk maps optimized for resource allocation and sampling prioritization (figure 1). The risk score in each STR grid is normalized to the interval [0,1], and subsequently used as basemap for optimized resource allocation and sampling prioritization.

In contrast to risk-factor selection for RBS calculation, there were insufficient data, initially, to justify informative weights for risk factors in California; therefore, the original model was run with all risk factors at equal weighting. Since the initial run, the weights for the model parameters have been recalibrated and refined after each round of data collection to improve model predictive accuracy and reliability, and new risk scores will continue to be assigned to the STR grid as the HLB epidemic develops. Figure 1 shows a series of maps over time for the southern California region, with risk values indicated by colour scale from low (blue) to high (red). The initial detections of HLB in the Hacienda Heights and San Gabriel areas of greater Los Angeles, and subsequent clusters of infection in Los Angeles, Orange, Riverside and San Bernardino counties have all been within STR grid squares assigned high to very high risk status from the earliest rounds of risk calculation.

For operational purposes, the output from the RBS calculation is used in the next cycle (usually 2 or 3 cycles per year) of the survey to identify the STR squares to be surveyed, with selection being biased toward squares with highest risk values. However, a 5% proportion of low-risk squares can be included as a negative validation of the risk assignment. The exact number of squares to be sampled and the details of the sample are decided through deliberation between the risk modelling team and the resource managers working for CPDPC in the CDFA. The resource managers provide up-to-date information on human resource availability and other logistics in each cycle in an effort to maintain balance between survey coverage and sampling intensity according to the RBS model.

The RBS has provided the basic quantitative underpinning for the HLB management programme in California for the last 7 years, successfully identifying areas of high risk for HLB introduction and development, and directing programme resources to maximize detection. The RBS is intended to place the surveillance teams in the areas with the highest probability of infection. However, it is left to the regulatory agencies to determine sampling and assay protocols, which can strongly influence detection/confirmation. As of 15 January 2019, 1031 trees infected with CLas have been detected and confirmed in residential southern California by applying the RBS. It is worth noting the issues that have had to be resolved in making the process work; all of these have been operational rather than directly related to the risk modelling itself.

In order for the entire procedure to work, it is necessary for the field data collected in each survey cycle to be passed to the modelling team quickly enough for updated risk calculations to be used in resource allocation decisions. *It is hard to overstate how much preparatory work should be invested in data exchange protocols, particularly if different agencies are responsible for collecting data and providing risk calculation*. Some, but by no means all, of the issues that might need to be dealt with ahead of time include:

— having agreement to allow data collected for regulatory purposes to be passed to a third party for analysis;
— compliance with protection of identity laws, if the data contain information that allows individual properties to be identified;
— clear specification of which data are required for risk calculations;
— assignment of responsibilities for data exchange timeliness and quality assurance to specific individuals at the data-generating and data-receiving ends of the partnership;
— and regular oversight of the process by programme management to avoid delays at potential recurring bottlenecks in the data collection to risk calculation to resource deployment loop.

4. Re-evaluation of surveillance logistics: optimizing resource allocation to programme components

With the RBS established as the foundation of the programme, a further series of operational issues has arisen over time. The CPDPP annual budget, including all grower-generated, state and federal funding, is currently in the order of $40 M. While this appears a significant sum, translated into human activity, equipment, laboratory costs and other operating expenses, it is a modest budget with which to suppress the spread of HLB in a region as large and complex as California. The key issue facing decision-makers is essentially a classical economic problem of how to allocate scarce resources to optimize a desired outcome. Two related resource allocation questions, in particular, recently emerged as high priorities for decision-makers.

The first question concerns the allocation of sampling resources between delimiting surveys around new disease detections and continuing the RBS across the selected set of STR squares in each cycle of sampling. Until recently, the regulatory response called for the imposition of an 800 m quarantine zone around HLB detections. The delimitation sampling required to establish the size of the infection cluster, and therefore the location of the quarantine boundary, is considerable and entails moving survey staff from the RBS to the delimitation survey. The trade-off that results is between coverage of the wider area that needs to be sampled (via the RBS) on the one hand, and, on the other, the rate of detection and delimitation of infected areas along with the associated removal rate of inoculum from the epidemic. The question posed by the CPDPC to the epidemiology team has two parts:

A. Would a smaller delimitation radius around each new detection significantly reduce the detection efficiency of the delimitation surveys?
B. Is it possible to derive an estimate of the probability of HLB-infected trees in each STR square and the probability of detection by the RBS to gauge the benefit of moving resources from delimitation surveys to the RBS?

The epidemiology team has been able to provide answers to both questions.

(a) Part A: reducing delimitation radii

The history of positive detections in each infection cluster (where an infection cluster is defined as a distinct 800 m radius around one or more infected trees) was reconstructed

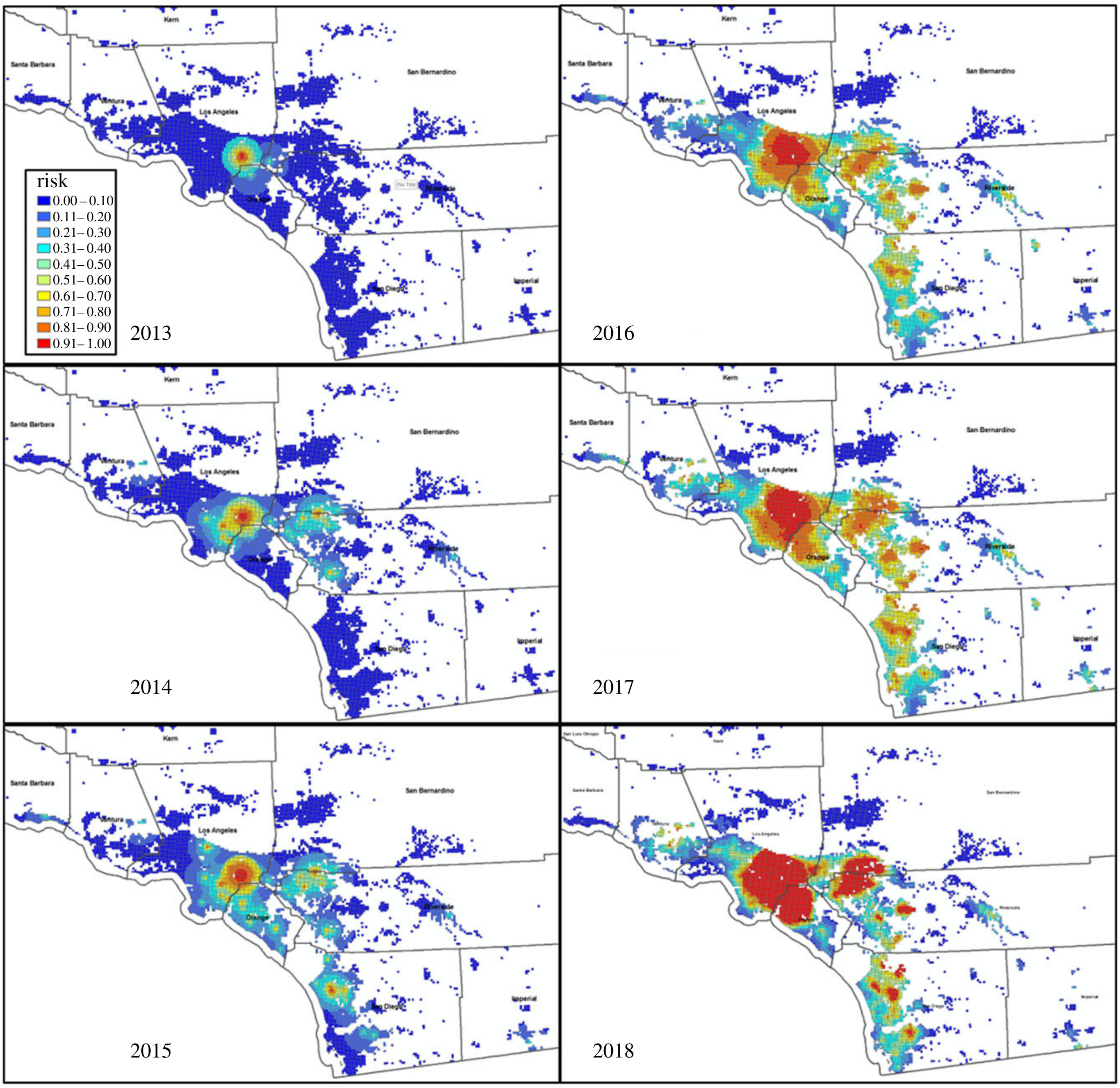

Figure 1. A progression of RBS risk maps for the HLB epidemic in southern California over the period 2013–2018. (Online version in colour.)

from the database maintained by CDFA. Samples both of confirmed CLas positive trees and of ACP were used to reconstruct the detection timeline within each cluster. By expressing the cumulative distribution of detections as a function of distance from the initial detection, it was possible to show in simulated data-resampling experiments that reducing the radius of the delimitation survey from 800 to 400 m would result in the detection of greater than 90% of the CLas-positives detected by the larger radius. For some of the clusters, the sampling effort required to sample the smaller area would be only 25% of that needed for the larger area. Figure 2 shows the temporal reconstruction of detections in one disease cluster and the summarized outcome of the data-resampling experiments used to simulate disease detection efficiency with reduced delimitation radii. The findings were reported to the Science sub-committee of the CPDPC in July 2018 and the CPDPC voted to reduce the delimitation survey radius to 450 m at its July meeting; 450 m was chosen rather than 400 m in an attempt to add additional assurance of disease detection and control.

(b) Part B: estimating state-wide disease incidence

The resources released by reducing the area of delimitation surveys should be available for disease surveillance in the RBS. An operational question for decision-makers, however, was what difference the extra resources might make to disease detection. To answer that question, it was necessary to provide estimates of the probability of infected trees in each STR grid square, as a basis for estimating detection rates. Through RBS deployment and data collection, the number of samples and the number of HLB detections are recorded each survey cycle, and estimates of the number of residential citrus trees are updated for each STR. In STR grids where sufficient information is available (i.e. more than 1% survey coverage occurs), predictions can be made on HLB incidence based on the data collected and the detection accuracy, with the underlying assumption that infected trees are homogeneously distributed. Figure 3 summarizes the statistical approach for estimating the probable HLB incidence range for each STR in California, and provides a snapshot of predicted incidence ranges for southern California using qPCR as the detection technique,

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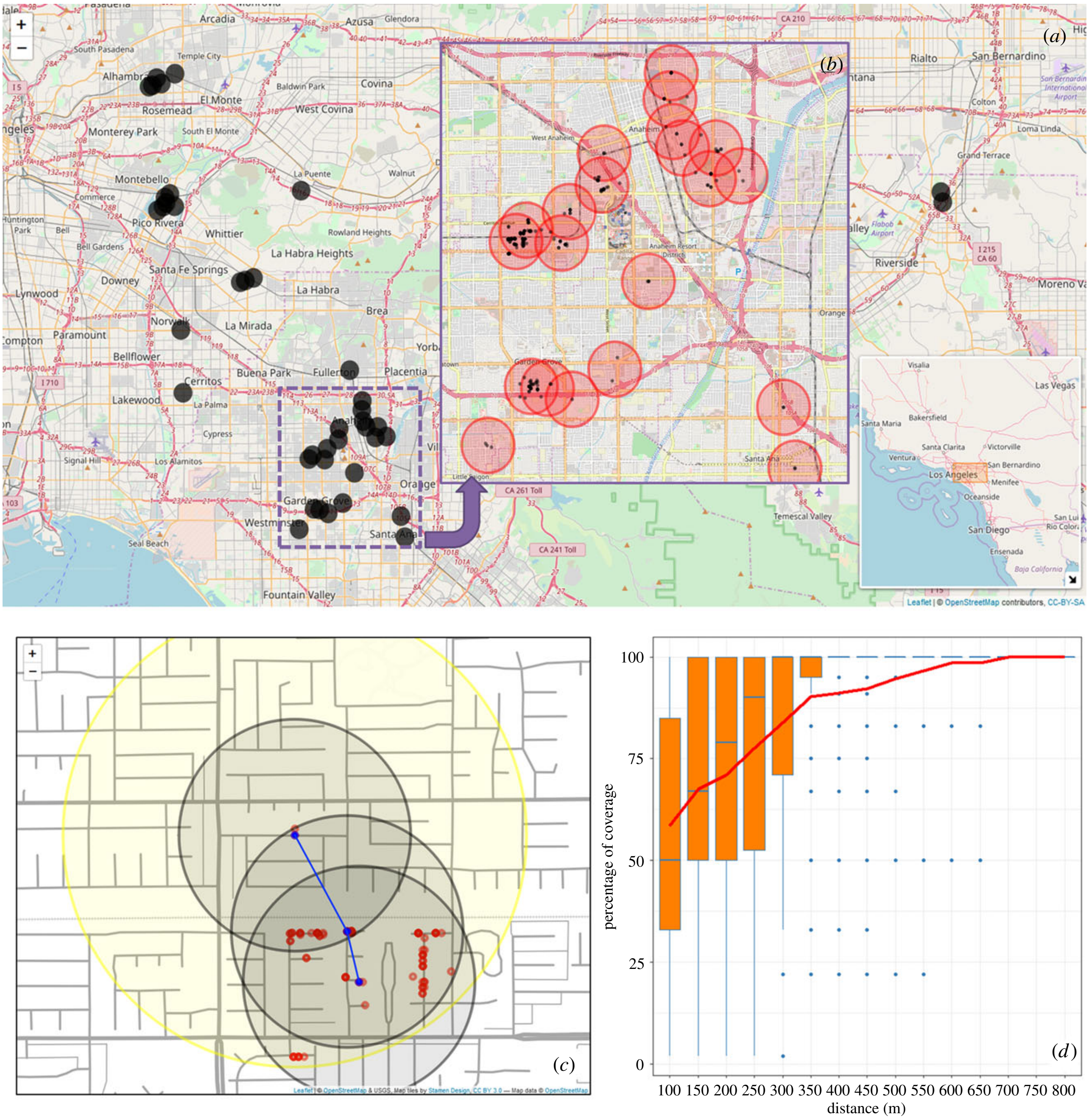

Figure 2. (*a*) Spatio-temporal cluster analysis identified 41 HLB clusters in southern California when using an 800 m delimitation distance. (*b*) High-resolution inset image of HLB clusters in Orange County. (*c*) Reconstructed timeline of HLB-positive tree detections in one infection cluster in Anaheim, CA. The large, yellow circle identifies the original 800 m delimitation survey; the smaller, black circles demonstrate a 400 m delimitation survey, starting with the initial find and iteratively capturing all confirmed *C*Las+ trees. (*d*) Summary results for data resampling simulation experiments showing the cumulative percentage of detections achieved by delimitation surveys of different radii using all known detection data from California from the period 2012 to December 2017. The simulations indicate that greater than 90% of all known positive trees would have been detected by delimitation surveys of 400 m radius; the eradication programme operated with a radius of 800 m during this period. (Online version in colour.)

with a realized detection accuracy of 25%. This is the assumed detection efficacy of the sampling protocol for individual trees, based on independent experiments (T Gottwald 2018, unpublished data, see the electronic supplementary material).

5. Exploring the feasibility of changing regulatory policy: defining exposure to the pathogen—the first step to changing the process of mandatory tree removal

The second major question posed by CPDPC follows from the two-part first question. One of the main uses of human resources in the delimitation surveys is in collecting plant and ACP samples for diagnostic laboratory tests. Trees inside 800 m quarantine areas that initially produce negative qPCR test results are added to a watch list and resampled at regular intervals to determine whether they have become CLas+. As the number of detections grows, and new quarantine areas are declared, the number of trees on the watch list grows with the area under quarantine. It is estimated that garden citrus trees compose approximately one-quarter to one-third of all citrus in the state. In southern California, 40 to 50% of properties have a citrus tree of some kind, with the median number of trees per property estimated at just over two trees; the watch list of potentially infected trees in urban gardens is now in the tens of thousands.

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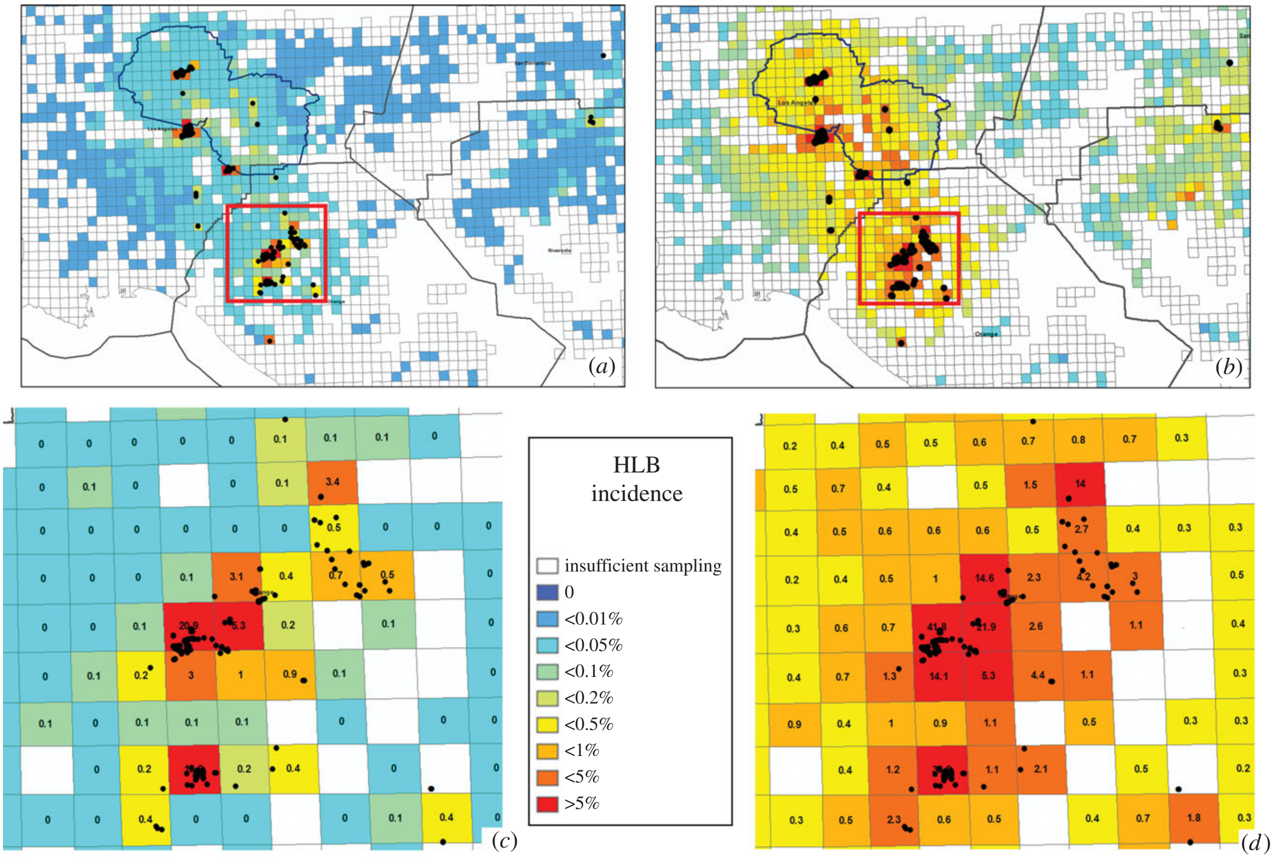

Sampling size	Detection probability (Actual infected tree % within STR * sampling accuracy)											
	0.01%	0.10%	0.25%	0.50%	0.75%	1.00%	2.50%	5.00%	7.50%	10.00%	25.00%	50.00%
1	0.000	0.001	0.002	0.005	0.008	0.010	0.025	0.050	0.075	0.100	0.250	0.500
2	0.000	0.002	0.005	0.010	0.015	0.020	0.049	0.098	0.144	0.190	0.438	0.750
3	0.000	0.003	0.007	0.015	0.022	0.030	0.073	0.143	0.209	0.271	0.578	0.875
4	0.000	0.004	0.010	0.020	0.030	0.039	0.096	0.185	0.268	0.344	0.684	0.938
5	0.000	0.005	0.012	0.025	0.037	0.049	0.119	0.226	0.323	0.410	0.763	0.969
10	0.001	0.010	0.025	0.049	0.073	0.096	0.224	0.401	0.541	0.651	0.944	0.999
20	0.002	0.020	0.049	0.095	0.140	0.182	0.397	0.642	0.790	0.878	0.997	1.000
30	0.003	0.030	0.072	0.140	0.202	0.260	0.532	0.785	0.904	0.958	1.000	1.000
40	0.004	0.039	0.095	0.182	0.260	0.331	0.637	0.871	0.956	0.985	1.000	1.000
50	0.005	0.049	0.118	0.222	0.314	0.395	0.718	0.923	0.980	0.995	1.000	1.000
60	0.006	0.058	0.139	0.260	0.363	0.453	0.781	0.954	0.991	0.998	1.000	1.000
70	0.007	0.068	0.161	0.296	0.410	0.505	0.830	0.972	0.996	0.999	1.000	1.000
80	0.008	0.077	0.181	0.330	0.452	0.552	0.868	0.983	0.998	1.000	1.000	1.000
90	0.009	0.086	0.202	0.363	0.492	0.595	0.898	0.990	0.999	1.000	1.000	1.000
100	0.010	0.095	0.221	0.394	0.529	0.634	0.920	0.994	1.000	1.000	1.000	1.000
250	0.025	0.221	0.465	0.714	0.848	0.919	0.998	1.000	1.000	1.000	1.000	1.000
500	0.049	0.394	0.714	0.918	0.977	0.993	1.000	1.000	1.000	1.000	1.000	1.000

(*e*)

statistical approach to estimate HLB incidence

observed event: number of HLB+ trees detected in each STR

1. Using binomial theory, estimate the chance of the observed event under different incidence scenarios and the accuracy of the detection technique implemented to construct the potential HLB incidence range.
2. Adjust incidence range based on available information: STR risk and sampling density; STRs with less than 1% sampling coverage are not considered (insufficient information).

(*f*)

Figure 3. Estimated minimum (*a*) and maximum (*b*) HLB incidence for each STR in southern California. (*c*,*d*) Higher resolution of estimated incidence range for Orange County subregion with detections from the RBS identified (dots). (*e*) Sampling efficacy table predicting the probability of finding at least one CLas+ tree given the sampling effort and detection probability, using the binomial theory. (*f*) Summary of the statistical methodology for estimating HLB incidence ranges for each STR using the RBS, and subsequent data collection via survey deployment. (Online version in colour.)

The rate of growth in the size of the watch list derives from the way State Agriculture Code is interpreted for regulatory purposes. The state's right to take action against noxious organisms is established by this code, which is itself drawn from federal statute. The definition of 'infected' that it uses is based on that established by the United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA-APHIS-PPQ, 'PPQ' for brevity) under its mandate as the national plant protection organization. Regulatory authority established by PPQ is always based on *direct* confirmation of the presence of the quarantine organism. In the case of HLB, this means that the definition of 'infected' is based on confirmation of the presence of pathogen DNA by qPCR. Because of the high probability of false negatives, caused by the variable interval between initial infection and the time when CLas becomes widespread in a tree, increase in the number of trees on the watch list for re-testing is essential to allow useful state removal activities, compliant with the strictest interpretation of the Code.

Despite the interpretation that has historically been used, however, the actual wording of the California Agriculture Code offers a potential solution to the problem of the growing watch list. The relevant section of the code (article 4, §5762) states:

> Any pest with respect to which an eradication area has been proclaimed, and any stages of the pest, its hosts and carriers, and any premises, plants, and things infested or infected ***or exposed to*** infestation or infection with such pest or its hosts or carriers, within such area, are public nuisances, which are subject to all laws and remedies which relate to the prevention and abatement of public nuisances.

Thus, state law in California allows the state regulatory agency (i.e. CDFA) to take action against noxious organisms, or locations that may harbour them, when they have been *exposed to* infestation or infection. It seems safely arguable that 'exposure' concerns possibility rather than confirmed fact.

Hypothetically, this interpretation allows a solution to the resource limitation issue by reducing the need for a re-testing programme on an ever-increasing number of trees. If a definition of '*exposed to*' could be made along these lines, trees within an exposure radius around confirmed positive detections could be removed (i.e. culled) without testing, freeing up resources to allocate to the RBS or establishing new delimitation surveys. There are also added potential benefits of removing undetected sources of inoculum from the epidemic and reducing the host density in high-risk areas. The question posed by the CPDPC to the epidemiology team was whether a suitable definition of exposure could be derived from the available data in California. The question was similar to that which underpinned the Asiatic citrus canker eradication programmes in Florida and Brazil [16,17].

The initial analysis of this problem was similar to that used in Part A of the earlier question. Data from the time-course of infections were used to characterize each infection cluster according to the cumulative proportion of known positives occurring with time and distance from the first detection. These analyses revealed that while some clusters were relatively dense—having large numbers of infected trees in close physical proximity, and consequently confirmed to be infected over a short time from the start of sampling—other clusters were more diffuse, with infected trees that were more widely spaced, and which consequently took longer to be detected. Since culling is itself resource-intensive, it is only likely to be feasible for dense clusters, where the total number of trees inside the exposure radius will be relatively small. This sets a useful constraint for the rule-making process to turn the definition of exposure into operational phytosanitary activities, but it leaves the issue of the definition of exposure, *per se*, unanswered.

Ideally, a definition of exposure used in rule-making would be based on definitions in published peer-reviewed analyses. Such definitions do exist (e.g. [18]), but key data on ACP numbers needed to adapt the definitions for urban California are lacking. This is because once a region is considered to be 'generally infested' with psyllids, no further estimates of vector population density tend to be made.

However, as already noted, there are accurate records of verified infected hosts. This allows the possibility of exploiting the fact that the vector and host dynamics are coupled, to use the infected tree data as a proxy for the missing psyllid data, and to construct the definition of exposure primarily from the disease incidence data, knowing that pathogen spread is essentially impossible without the involvement of the vector. The basic concept is well known in the analysis of population time-series data [19,20]. The implicit involvement of the vector in disease spread allows the time-series of disease detections to be expressed in terms of its own history alone, even though the underlying process, in which the vector exposes the trees to infection, involves coupled dynamics between two populations. In other words, precisely because the system has a biological interdependence between vectors and diseased hosts, we can express exposure in terms of the outcome of that interaction, even when the outcome is characterized by the numbers of infected hosts alone.

6. Using the new definition of exposure: a second step in changing the process of mandatory tree removal

Despite lacking primary data on vector populations, the modelling team can yet use details of observed psyllid behaviour to draw up guidelines for tree removal and managing watch lists.

Figure 4 shows the distribution of density of HLB infections around 659 known infected trees in southern California, when a radius of 170 m around the infected trees is considered. To give an illustrative example to aid interpretation, approximately 70 of the infected trees had no other infected trees (indicated by 0 on the horizontal axis) within 170 m. Bars toward the left end of the figure represent conditions of relatively sparse infection, while those toward the right hand end are characteristic of denser infection clusters. Clusters toward the right-hand end of the scale would be more likely targets for a removal policy based on exposure than those toward the left.

The substitution of 'exposed' for 'infected' and the use of cluster observation data to determine the likelihood of exposure potentially allow a shift from a strategy of spot-removal of individual trees, verified as infected, to a strategy of clearing dense clusters of trees, known to be exposed and therefore almost inevitably infected. However, such a shift might trigger legal challenges to the authority of the tree removal programme. A citrus canker eradication programme in Florida that used a comparable approach was successfully challenged in class actions brought by homeowners [16].

A hypothetical example of how this process could, nevertheless, be made operational is given in the supplementary material. The issue of whether the approach could be feasible is under active discussion by the CPDPC with advice from CDFA staff and the modelling team.

While homeowners with citrus trees on their properties have in the past in Florida [16] mounted determined resistance to unwelcome phytosanitary regulation, and might do so again in the future in California, such a response is a typical example of the conflict between private utility and public welfare in disease management; there are obvious parallels with the desire to opt out of public vaccination programmes for communicable diseases. In forcing a choice between private benefits and a wider public good such conflicts have similarities to many of the choices faced by commercial California growers, who are regularly forced to resolve trade-off problems in the course of the HLB epidemic in California.

7. Participatory analysis of the risk of disease spread and associated quarantine policy

One of the most problematic aspects of a disease like HLB is that it forces growers and regulators to make inter-temporal trade-off choices between current and expected future benefits; that is, it requires incurring immediate costs to protect against possible, larger, future losses. The removal of infected but fruit-bearing trees is one such trade-off [21]; imposing quarantines and requiring mitigation measures on fruit transport is another.

When citrus fruit is harvested, it is loaded in bulk on trailers for transportation to packing houses, where it is cleaned

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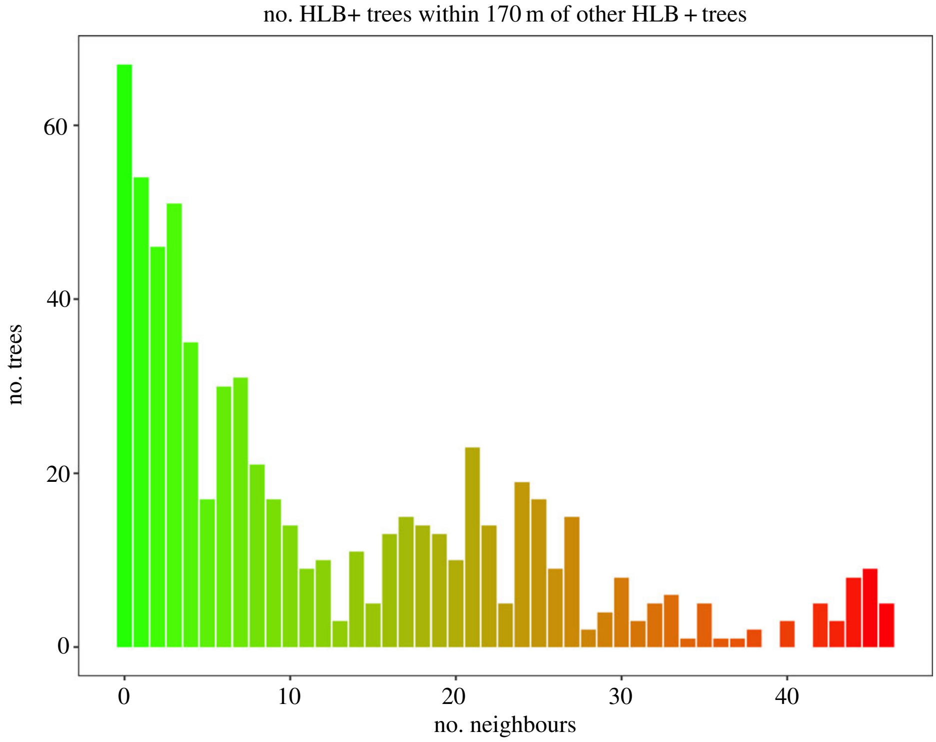

Figure 4. The distribution of density of infected citrus trees within 170 m of newly detected, infected trees. Note that many newly detected trees have no, or few, other infected trees within 170 m at the time of detection, but several have in the order of 20–30 infected close neighbours, and there is a set of trees that have 40 or more infected neighbours. (Online version in colour.)

and packaged for sale. A few packing houses handle the majority of the state's production, meaning that fruit can travel hundreds of kilometres to be processed. The risk of spread of ACP along with bulk citrus loads has been known about for several years, and has been quantified based on observations collected in Florida [15,22]. During the period 2014–2017, the whole of southern California was under quarantine for ACP while only selected areas of northern California, associated with isolated psyllid detections, were quarantined. The incidence of psyllid detections in northern California increased steadily during that period and there were calls from the industry for a state-wide quarantine to be declared and for within-state mitigations associated with fruit movement to be stopped, on the basis that the existing regulations were costly and failing to prevent incursion of the vector into the northern region.

Prioritizing long-term viability for the industry as a whole, over maximizing immediate profitability for individual growers and packers, the epidemiology team argued against setting a single state-wide quarantine. We used the relationship between the presence of transportation routes and the risk of ACP and HLB presence estimated in Florida to illustrate the association between ACP detections in northern California and major fruit transport routes. A briefing paper was produced which recommended that the state be subdivided into more zones, and mandatory covering of bulk citrus loads to be initiated, along with mitigation steps such as treatment of orchards with insecticide and fruit cleaning to remove leaves, stems and insects, prior to road transport of bulk citrus. CPDPC voted to request the necessary rule-making, and CDFA used emergency rule-making provisions to pass the new regulations, which came into effect in January 2018. Figure 5 shows the locations of the seven zones demarcated by CDFA and the initial risk matrix produced by the epidemiology team for fruit movement between pairs of zones.

When the resulting bulk citrus movement regulations were initially implemented, CPDPC approved a uniform requirement for mitigation measures before fruit could be moved between zones. With the basic policy in place, there has been a steady demand from some groups of growers to make the regulations more responsive to perceived local risk levels and to institute flexible mitigation requirements for different zones.

In response to these mitigation requests, CPDPC asked the epidemiology group to re-evaluate the risk of moving bulk citrus between the regional quarantine zones and to provide evidence upon which any potential changes to the regulations could be based. The epidemiology group developed a pilot qualitative risk model, using the federal framework for pest risk analysis as a guide.

The analysis of the risk posed by fruit transport highlights the recurring theme of the need to deal with a 'fluid' situation, in terms of the features of analyses needed for rapid programme support, but also how the behaviour of decision-makers can contribute to the fluidity. On the first point, as with the starting situation for the RBS, the information required for a quantitative analysis of the risk of fruit transport was mostly unavailable. In both cases (which are typical of situations where empirical data are absent or inadequate for quantitative analysis), qualitative models built from expert knowledge were used as substitutes. This is accepted as an inevitable next-best option in many regulatory contexts [23] since 'a decision must be made'.

With respect to human behaviour, the objective for the analysis changed, iteratively, as decision-makers were exposed to the results of the work and their opinions changed accordingly. The initial balance of opinion in favour of removing internal state quarantines changed to acceptance of the need for increased quarantine zoning of the state when the evidence from Florida was presented to CPDPC; the acceptance of the quarantine zones and the accompanying uniform requirement

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risk: movement to \ movement from	zone 1	zone 2	zone 3	zone 4	zone 5	zone 6	zone 7
zone 1		low	low	low	low	low	low
zone 2	low		high	high	high	high	high
zone 3	low	medium		medium	medium	medium	medium
zone 4	low	high	high		high	high	high
zone 5	low	medium	medium	high		high	medium
zone 6	low	medium	medium	high	medium		medium
zone 7	low	low	low	low	low	low	

(*a*)

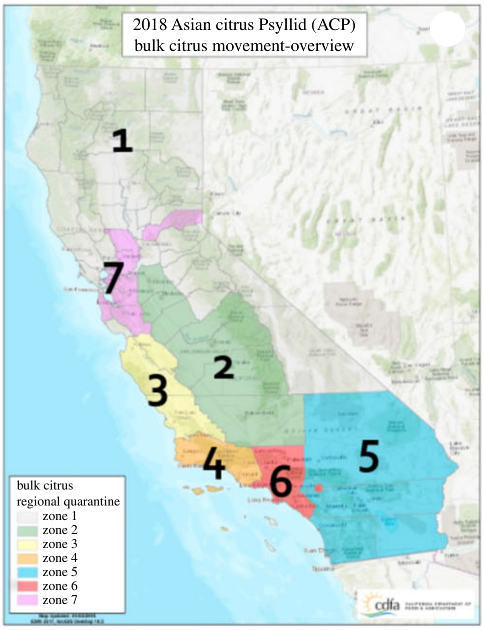

Figure 5. (*a*) Risk matrix for HLB associated with bulk fruit transport between different pairs of quarantine zone within California, depending on risk of infection in the zone of origin and magnitude of potential impact in the zone of destination. (*b*) Map of California showing the quarantine zone boundaries. The majority of commercial production is located in zone 2. All known HLB cases have been in zone 6. Note that zone 6 is discontinuous, with a small subsection (Riverside) encircled by zone 5. (Online version in colour.)

for mitigation of the risk of transport of ACP with fruit movement gave way to requests for a more nuanced policy based on a risk evaluation, once the cost and inconvenience of the initial regulations were experienced; the finding of the risk evaluation—that nearly all possible pairs of zones of consequence to the citrus industry were at high risk (because either the source had elevated risk status, or the potential impact in the destination zone was high, or both)—was questioned by some members of the CPDPC. This resulted in the current situation, in which the modelling team is facilitating an industry working group to evaluate the risk analysis, to adapt the model if necessary and to generate recommendations of further changes to the regulations for consideration by CPDPC.

8. Discussion

In a recent analysis of the role of human behaviour in the efficacy of disease control in agriculture, McQuaid *et al*. [24] noted:

> The success or failure of a disease control strategy can be significantly affected by the behaviour of individual agents involved, influencing the effectiveness of disease control, its cost and sustainability. This behaviour has rarely been considered in agricultural systems, where there is significant opportunity for impact.

The analyses described by McQuaid *et al*. [24] and the work described in this paper can be thought of as representing contrasting alternatives, lying towards opposite ends of a continuum of approaches, for dealing with the complexity of human behaviour in disease dynamics. The approach taken by McQuaid *et al*. [24] to address the need they identify can be characterized as strategic and external to the problem at hand. The modellers summarize the system, including human behaviour, in a mathematical framework aimed at broad understanding of the factors that determine the dynamics, and provide valuable strategic suggestions about potential interventions from the viewpoint of external observation. In contrast, the approach adopted in our efforts to support the CPDPC in California can be characterized as tactical and internal to the problem. The modellers analyse individual questions that arise from operational activities and deal with the human behavioural component of the dynamics through direct interaction with the decision-makers in the system of interest.

The strategic/external perspective has had considerable success in identifying guiding principles of disease management in botanical epidemiology [25–28], public health [29–31] and veterinary epidemiology [32,33]. The general principles of intervention that such strategic modelling approaches have yielded provide a useful framework for decision-makers in rapidly developing, invasive epidemics, such as the HLB problem in California, but do not often provide detailed information that can resolve operational questions. As McQuaid *et al*. [24] point out, variation in the behaviour of those responding to a disease outbreak further complicates the situation facing decision-makers attempting to manage regional resources. Here again, as with strategic modelling of disease dynamics, analyses that provide useful general insights into behaviour under risky conditions across a population [24,34,35] are less likely to be applicable to help decision-makers dealing with specific tactical decisions, with imperfect information, under time pressure.

In contrast to the clarity often available in the results of strategic modelling work, the type of analysis conducted in close programme support inevitably inherits much of the uncertainty that makes decision-making in these circumstances difficult in the first place. Rather than a unified analysis of the entire problem posed by the epidemic, what develops in such circumstances is a set of more-or-less distinct analyses, each focused on a particular issue. However, the questions addressed in the current support work are typical of those encountered in the response to invasive diseases. It is vital that we recognize the broad issues that the California HLB epidemic, and the response to it, share with comparable outbreaks and develop the methodology needed to include these general features in strategic epidemiological models, for the benefit of future decision-makers facing the same challenges. Good progress in this kind of integrative work has already been made [21,24,36–40]. A significant challenge faced by epidemiology is to integrate the valuable insights these analyses provide with close programme support work of the type described here.

Data accessibility. This article has no additional data.

Competing interests. We declare we have no competing interests.

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January – March 2021

The search for a better trap

In January, the Citrus Pest and Disease Prevention Committee (CPDPC) Operations Subcommittee asked DATOC to review available methods of trapping ACP and recent research on the subject. In March, we presented the results of our review to the Subcommittee. After querying the DATOC expert panel and a review of available literature, we found that there were a few methods which warranted further experimentation in California. Further work on this project has been moved to the Science Subcommittee.

Exploring the effectiveness of the residential control program

Modelling the effectiveness of huanglongbing control

DAOTC has been working with the CPDPC Science Subcommittee to explore how the effectiveness of the residential control program can be evaluated. In February, we presented the results of two projects aimed at answering this question. The first used the agent-based model, built by the epidemiology team at the USDA-ARS lab in Ft. Pierce, FL, to model huanglongbing spread from residential areas of Ventura counties into commercial orchards.

The second project used the Cambridge Modelling interface, developed at Cambridge University, to simulate spread over the greater Southern California region under different management scenarios. Both models indicated that a control program like the one currently utilized in California would slow disease spread.

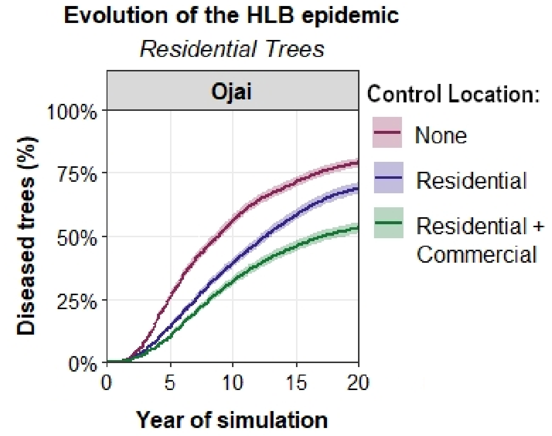

Figure 1. An excerpt of output from the agent-based model.

Classification of climatic suitability

Another part of our support work for the Science Subcommittee has explored the suitability of average maximum and minimum temperatures in different regions for ACP development. After completing this work for California, we were asked to expand our efforts to include Texas, Florida, and Brazil. With collaboration with researchers from Brazil, this request was completed and provided to the subcommittee; a concluding report was not involved as the results are part of an ongoing discussion.

Stakeholder Communication

In March, we received an updated sampling database from CDFA which was processed and added to our monthly updates on the data dashboard at www.datoc.us/data-dashboard. We have also implemented a new weekly update on DATOC's activities, which can be found on the homepage.

The search for a better trap: a review of Asian citrus psyllid trap technology research

Holly Deniston-Sheets[1]
Monique Rivera[2]
Rick Dunn[1]
Neil McRoberts[3]

[1]*Citrus Research Board*
2 Department of Entomology, UC Riverside
[3]*Quantitative Biology & Epidemiology Lab, Plant Pathology Dept., UC Davis*

Summary

In January, the CPDPC Operations Subcommittee asked DATOC to review available methods of trapping ACP and recent research on the subject. After querying the DATOC expert panel and a review of available literature, we cannot recommend any new technology for immediate utilization by the CPDPD. However, there are a few options which we can recommend be tested experimentally, including the use of “no mess” sticky cards.

Background

The Citrus Pest and Disease Prevention Division (CPDPD) is currently exploring the use of 3D traps in Southern California. These traps collect Asian citrus psyllid (ACP) into a preservative, allowing the insect to be tested for *Candidatus* Liberibacter asiaticus (*C*Las). The Operations Subcommittee asked the Data Analysis Tactical Operations Center to explore other trapping methods that the program could potentially use to broaden our understanding of vector dynamics and the vector/pathogen complex in California. We were asked to consider not just the current situation and efficacy, but any potential improvements in labor or processing, and how tools might be used in the future as the California situation changes.

Sticky Panel Traps

Despite a commonly encountered view that yellow sticky traps are a low-tech method of questionable efficacy, a substantial body of research, conducted over more than a decade, supports their use in monitoring Asian citrus psyllid populations. Although by no means a foolproof method, insect catches from sticky traps have been shown to be correlated with the presence or absence of field populations, population trends over time, and are better suited for detecting ACP at low-population densities than visual or stem-tap sampling (Hall, 2009; Monzo et al. 2015; Miranda et al. 2018). For monitoring ACP, sticky traps have been shown to be superior to other trap types, such as the Multi Lure trap for monitoring fruit flies, or the CC Trap (named for one of its inventors, Chang-Chi Chu) for whiteflies (**Figure 1**) (Hall et al., 2007).

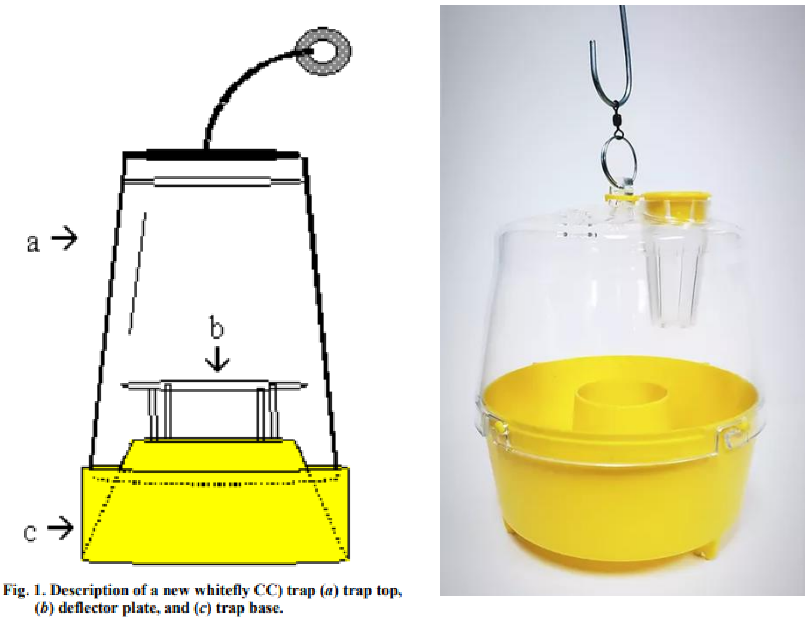

Figure 1. Left: CC Trap from Chu and Henneberry (1998). Right: multi-lure trap from betterworldus.com. https://www.betterworldus.com/products

The type of sticky trap to use has been extensively researched. Various shades of yellow cards have been compared with red, green, blue, white, and purple cards, to name just a few (Miranda et al, 2018. Hall et al., 2007, Sétamou and Czokajlo, 2008). Shades of yellow and lime green have typically performed best in these experiments.

Different types of adhesive have also been tested. Traps with a traditional sticky adhesive have been tested against traps coated with a pressure sensitive adhesive, and there was no difference in the number of trapped adults between the two (Hall et al., 2010). The latter type has the additional benefit of allowing the removal of ACP for *C*Las testing using Histo-clear, an orange-oil based clearing agent. ACP from traps exposed to up to 3 weeks of weathering in Texas have been successfully tested for *C*Las using this method with no apparent degradation in the proportion which test positive (Villegas, 2020). Other research from Brazil utilized ACP collected from yellow sticky traps to monitor the proportion of the population infected with *C*Las (Wulff et al., 2020).

Mesh laid over sticky traps has been explored as a method of reducing non-target bycatch and debris. One type of tested mesh did not significantly reduce ACP catch numbers and did significantly reduce non-target species and debris (**Figure 2**) (Sétamou et al., 2018).

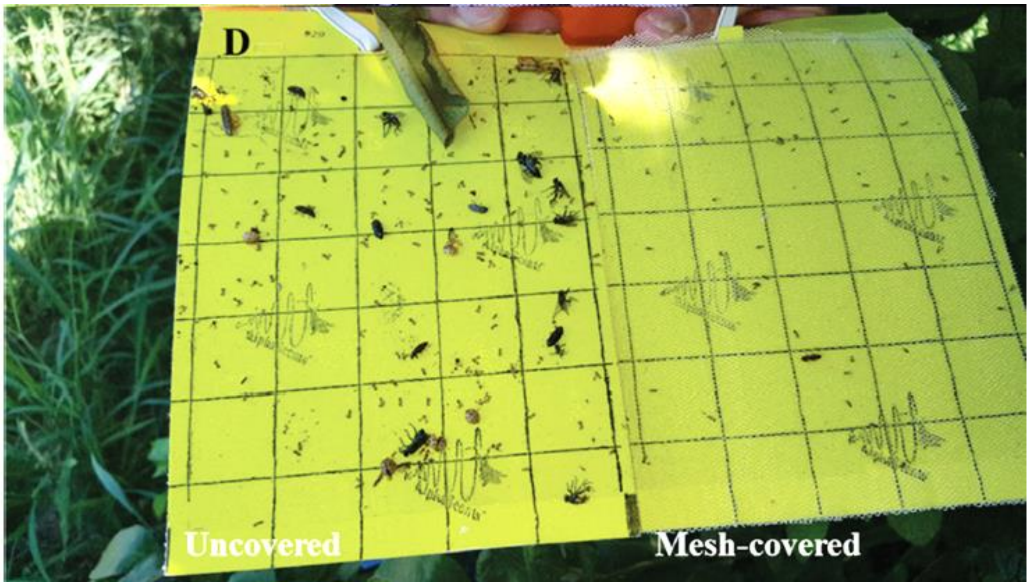

Figure 2. The difference in cleanliness between uncovered traps (left) and mesh-covered traps (right. From Sétamou et al., 2019 with modifications).

Research has also revealed how to optimize the location of sticky cards based on the preferred spatial niche occupation of ACP. Research has shown at what heights ACP commonly fly and documented their prevalence along the borders of groves, thereby indicating that traps should be placed on orchard perimeters (Setamou & Bartels, 2015) at a height of 1 – 2 m (Setamou et al., 2018) (**Figure 3**). Other research has found differing ACP densities based on the direction of the grove edge examined, but this has not yet been shown to be the case in California groves.

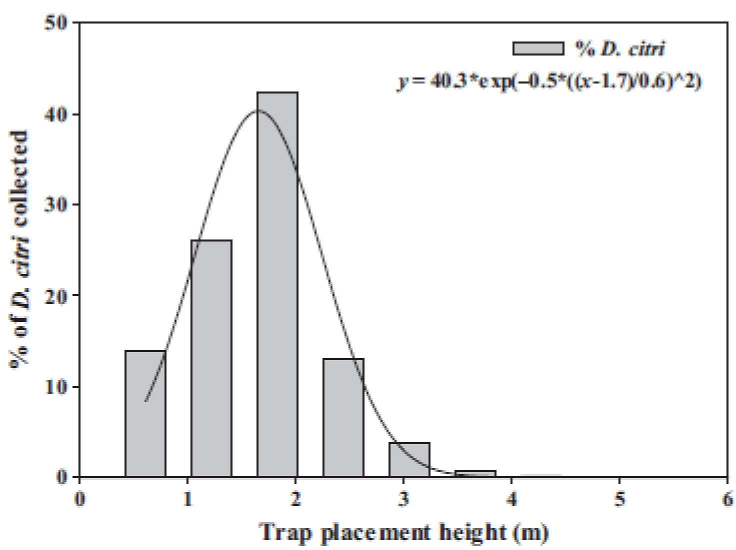

Figure 3. Percentage of ACP caught on traps placed at different heights along the perimeter of an orchard (from Sétamou et al., 2018).

Attractants, lures, and attract-and-kill traps

Much work has gone into research on attractants, both with yellow panel traps and with other types of traps, including attract-and-kill (AK) devices. Formic acid, acetic acid, and propionic acid have all been shown to be dose-dependent male ACP attractants, and traps using these chemicals as lures have been shown to catch significantly more male ACP than unbaited lures in field trials in California. Importantly, in an area of such low ACP density that visual confirmation of ACP infestation was nearly impossible, a slow-release acetic acid lure captured three times the amount of male ACP as a standard yellow trap (Zanardi et al., 2019).

Attract-and-kill devices have been tested with formic acid and acetic acid. Research has shown that these chemicals combined with para-cymene, a naturally-occurring terpene, induce psyllid feeding. This trio can be added with an insecticide to SPLAT (Specialized Pheromone & Lure Application technology), a slow-release wax used in several studies. When used with a three-dimensional trap, this can kill psyllids for 12 weeks (George et al., 2020) (**Figure 4**).

Other AK devices rely on ACP attraction to color. A two-dimensional device, made of plasticized PVC treated with B-cyfluthrin, was tested in Texas and was active for 8 weeks (Chow et al., 2019) (**Figure 4**).

Figure 4. Left: Example of one type of 3D trap covered with SPLAT and an insecticide (from George et al., 2020). Right: A 2D attract-and-kill device, conceived and developed by M. Sétamou and manufactured by Alpha Scents Inc. (West Linn, OR) (from Chow et al., 2019).

Other proprietary blends of host plant volatiles and ACP-produced compounds have been tested as lures in Texas and Florida; results indicated several blends significantly improved trap catches. Although California trials were inconclusive, this research resulted in a commercially available lure (Czokajlo, 2015; Alpha Scents Inc.).

Illumination has also been used to increase the attractiveness of traps to ACP. Setamou et. al (2012) showed that illuminating traps at night increased nighttime catches 5-fold compared with non-illuminated traps. Illumination has also been shown to increase trap catches in indoor environments set up to mimic citrus shipping containers (Mangan & Chapa, 2013).

Propylene glycol, a common food additive generally regarded as safe by the Environmental Protection Agency and the Food and Drug Administration (Thomas, 2008), has been tested in a salt mixture for preserving bacterial DNA in psyllids caught in the field. Research showed the preservative was effective for up to 6 weeks as compared with ACP tested either immediately or after being preserved at -20° C (Hall et al., 2018).

Many different types of 3D traps have been designed, and those that performed well in the lab have been tested in the field using propylene glycol as a preservative. Three trap types were tested in Florida, a "stem trap" and two versions of a "cylinder trap", against yellow sticky traps (**Figure 5**). Although the cylinder trap captured less ACP than sticky cards, they captured more psyllids than the stem trap, eliminate most bycatch, and preserved psyllids for polymerase chain reaction (PCR) testing (Snyder et

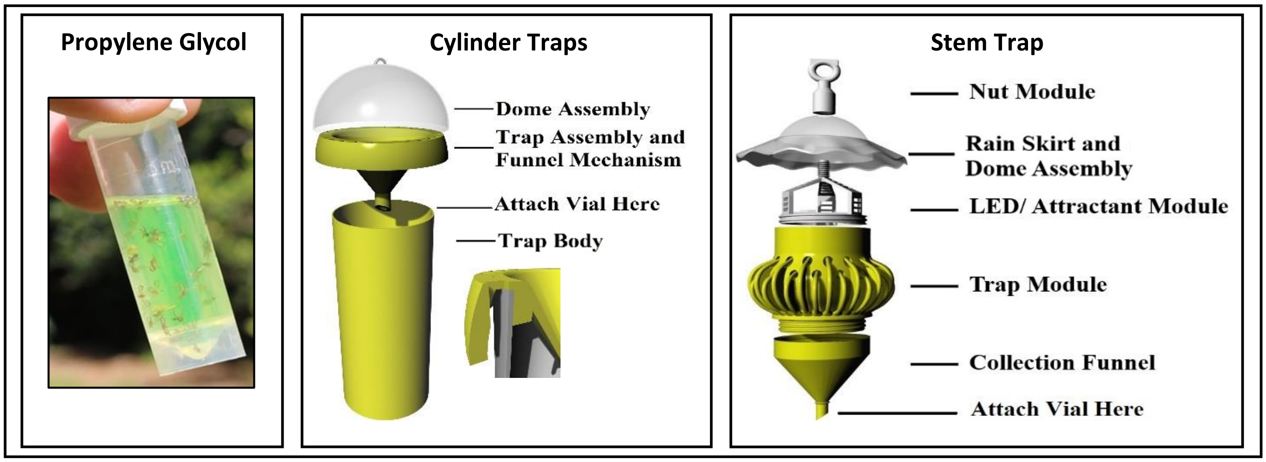

Figure 5. Examples of 3D printed trap designs tested in Florida (from Snyder et al., 2019).

al., 2019).

Suction

Sampling using suction devices has generally been shown to be an effective method of insect monitoring. However, it has various drawbacks which could limit its usefulness in large-scale ACP-detection programs; although it is the most sensitive technology for detecting low-density populations, the weight of the device, exhaust fumes from gas-powered devices, and the need for a power source for cabled devices limits its efficiency (Monzo et al., 2015; Thomas, 2012). The labor needed to sort and quantify samples is also a limiting requirement.

Bioaccoustics & Vibration

Some research has explored using bioacoustics or vibrational patterns as attractants or potential mating disruption. However, published research indicates that these are either still in the prototype stage or were not effective (Fernandez, 2020; Hartman, 2017).

Commercially available traps

A panel trap with a pressure-sensitive adhesive ("ACP Trap") is currently available from Alpha Scents. The cost is $1.39/trap for large orders (≥100 traps). Alpha Scents also offers a lure made with a proprietary formulation at the same large-order price (≥100 lures). We are unaware of any 3D or other

AK traps commercially available at this time. The contract price for traps currently used by California Department of Food and Agriculture (CDFA) is $0.28.

Concluding Remarks

At this time, we cannot recommend any new technology for immediate utilization by the CPDPD. However, there are a few options which we can recommend be tested concurrently.

Histo-clear has previously been used by the program to remove ACP from cards with a traditional adhesive, but there were practical limitations: it was labor-intensive, quality-control failures were more common than testing ACP collected into a preservative, and ACP on cards had to be identified by appropriate CDFA entomologists before they could be tested by the lab. However, research results testing ACP off of yellow traps with a "no-mess" adhesive are encouraging. Testing ACP from "no-mess" cards could be evaluated in California to determine if the process is superior to testing off of standard traps. Such an evaluation should include not just PCR results, but also the cost of the cards and the labour and timing involved in identification and removal of insects from the cards. If this method proves adequately suited for detecting *C*Las, but inferior in terms of labour or cost, such a technique could be deployed only where the usefulness of additional information on *C*Las in the vector population would outweigh the additional costs.

Such a trial could be run concurrently with collection methods directly into a preservative, as is the case with 3D traps, and compared with standard yellow sticky traps for monitoring total numbers caught. Likewise, the effectiveness of lures in California could also be evaluated. Lures could be useful in areas of low population density or where early detection of ACP is a priority, like Kern County, where the additional cost could be justified by the need for a more sensitive detection method.

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May 20, 2021

Citrus Pest and Disease Prevention Division
Attn: Victoria Hornbaker
1220 N Street
Sacramento, CA 95814

Dear Citrus Pest and Disease Prevention Division:

On behalf of the Citrus Research Board of Directors, CRB lends its support for the continuance of the California Citrus Pest and Disease Prevention Program. Since 2017, the Program has continued to further its mission in supporting the citrus industry's fight against invasive pests and diseases, particularly against the Asian citrus psyllid and huanglongbing. During its time, the Program has identified and removed over 2,300 CLas-infected trees from residential areas across the state and continues to regularly engage local communities about best practices to prevent the spread of huanglongbing and preserve our state's citrus industry.

The Program has worked to reduce the size of treatment areas and thus reduce program costs while increasing the timeliness of treatments to mitigate huanglongbing more effectively throughout the state. Program funds continue to be leveraged at the state and federal level with more than half the Program revenue coming from these sources to ensure growers' contributions to the Program are maximized. Despite the languishing industries of Florida and Texas in the wake of huanglongbing, California's industry has continued to grow through the unwavering support of our various industry partners and programs, all committed to ensuring the survival of our industry.

Sincerely,

M. L. Martin

Marcy L. Martin
CRB President

217 N. Encina Street, Visalia, CA 93291 | office: 559.738.0246 | PO Box 230, Visalia, CA 93279 | citrusresearch.org

Integration of scientific analysis into the activities of the California Citrus Pest and Disease Prevention Program

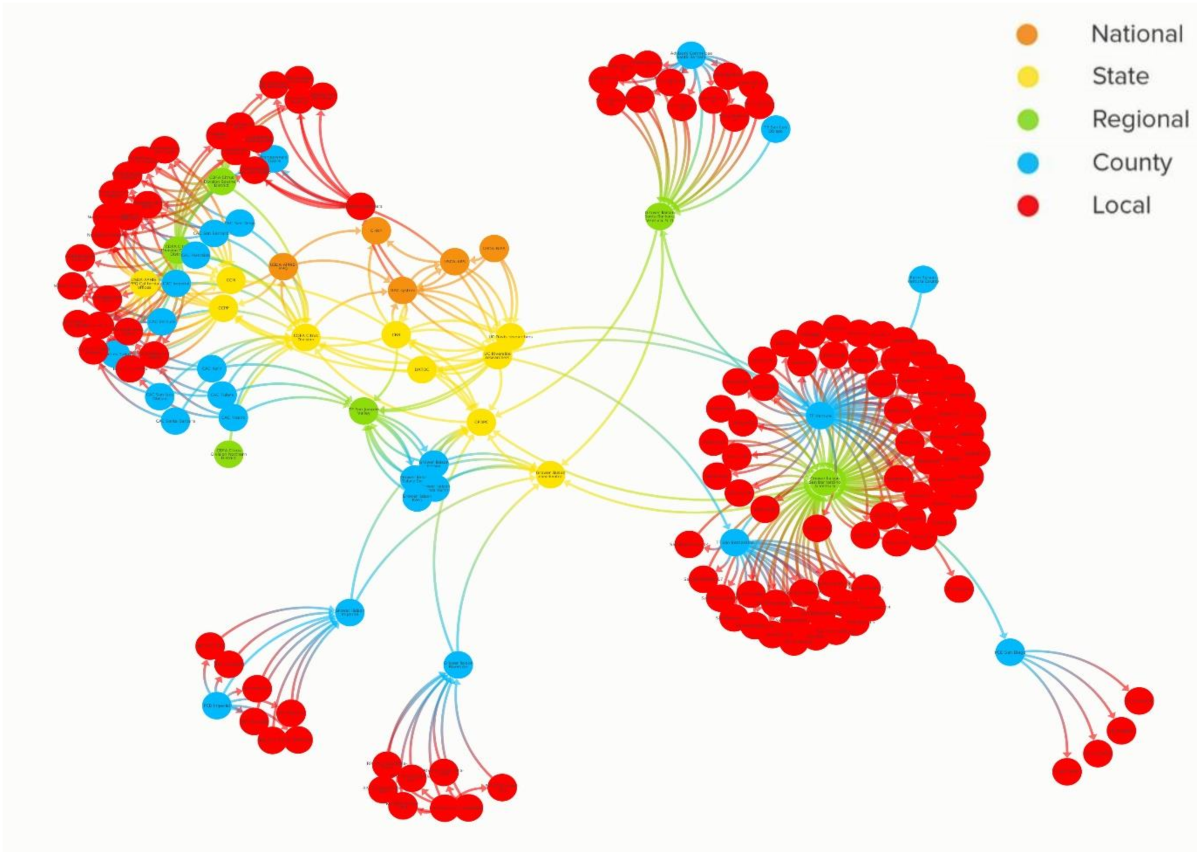
Neil McRoberts[1], Sara Garcia Figuera[1], Brianna McGuire[1], Weiqi Luo[2], Drew Posny[2], Holly Deniston-Sheets[3]

[1] *Quantitative Biology & Epidemiology Research Group, University of California, Davis, CA*
[2] *USDA Agricultural Research Service Horticulture Research Lab, Ft Pierce Florida, and North Carolina State University*
[3] *Data Analysis and Tactical Operations Center, Citrus Research Board, Visalia, CA*

Introduction

The Citrus Pest and Disease Prevention Program (now a Division, or CPDPD) provides a unique approach to disease management in California citrus, which, over time, has allowed the overall California response to develop into an integrated and comprehensive strategy, which has been more successful than any isolated effort. In addition to the direct work carried out by the Division, such as surveying for disease and insect pests, the structure of the Division- comprising California Department of Food and Agriculture (CDFA) staff, a committee of industry professionals, and grower liaisons, all partnered with scientific input from nationwide expertise- has served as the organizing framework for most of California's activities aimed at managing the risk of disease, especially Huanglongbing (HLB), in commercial citrus orchards.

This idea is well-illustrated by the network diagram on the next page, which shows connections between different aspects of the overall response program from a national (orange) to local level (red).



A graphic representation of the network of interconnected participants associated with California's response to huanglongbing and the Asian citrus psyllid.

Formal Program Evaluations

One of the most critical and difficult aspects of the successful management of an invasive plant disease is management of the "public goods" aspect. Public goods are the shared benefits that arise when coordination of individual efforts leads to a better outcome for everyone. Because the benefits of individual growers' efforts may spill over to their neighbors, there is always a balance to be achieved between the good accomplished by a program, the costliness of the program, and the requirement that individuals participate. There is a significant body of work detailing how such a management program should be structured for a high probability of success, and in a recent comparative analysis of HLB management responses in different areas of North, Central and South America, it was concluded that the program in California displays all the attributes required for success [1,2]. The Division in particular either contains those required aspects within its structure, or links other required aspects to the management program, thereby offering an efficient "institutional fit" between the program and its goals.

The network structure and the data collected to evaluate on-going program performance allow independent scientific analysis of many aspects of the program's function, from area-wide vector management [3] to likely adoption patterns of new technology by growers [4]. These analyses are used to inform the outreach strategy, which is itself a collaborative effort involving CDFA staff, UC academics, grower liaisons, growers, and the contracted public relations consultancy Nuffer, Smith and Tucker.

Integration of scientific analyses

The incorporation of evidence-based decision-making processes into the Division since its inception is likely a key element of California's success thus far. The Division's reliance on scientific input to assist in decision-making for both operational and strategic aspects of its mission has allowed the program to evolve over time with the best interests of the industry at the forefront of every decision. The Division has utilized expertise from departments in multiple universities, including the Plant Pathology Department at UC Davis, the Entomology Department at UC Riverside, and the Economics Department at CSU Sacramento, in addition to expertise from the United States Department of Agriculture (USDA) Agricultural Research Service, particularly the Horticulture Research Lab at Ft. Pierce, FL. In 2016, with Division funding, the Citrus Research Board and UC Davis established DATOC to act as a platform for the interactions between academic and government researchers working on HLB in different parts of the United States and the industry professionals that make up the Division's working committees. More information can be found in a 2019 overview of the science/decision-making interaction [5], and this as well as other reports issued by DATOC on relevant topics are included with the Annex materials. A few examples of the Division's incorporation of scientific input into operational and strategic decisions are listed below.

Evidence driven decision making processes in the California Citrus Pest and Disease Prevention Division
• Requiring fruit trucks to be tarped based on repeated detections of ACP adults along fruit transportation routes and research showing adult ACP move in fruit shipments
• Creating and reviewing bulk citrus quarantine zones based on pest risk analysis criteria and shipping logistics
• Reducing the survey area around an HLB-positive tree based on an analysis of past detections and the estimated probability of a new detection at different radii
• Updating the criteria to determine which residential neighborhoods qualify for insecticide buffer treatments, based on a dynamic analysis of participation in area-wide management treatments in nearby Psyllid Management Areas (PMAs) or Pest Control Districts (PCDs)
• Analyses of the effectiveness of different components of the disease and vector control programs in southern California.
• Analysis of the available technology for ACP trapping and recommendations for the frequency of trap collection for different areas of the state based on climatic suitability for ACP and patterns of past detections.

Many of these decisions have required extensive mathematical and statistical analyses, capabilities that are provided to the program in part through interaction with DATOC. The program and related analyses have used two tools in particular which fit these categories: the Risk-Based Survey (RBS) and scenario-based modeling tools.

Pathogen Detection: Risk-Based Survey

The RBS has been used to guide the location and intensity of state-wide sampling activity for HLB and ACP detection. Activity is guided using a predictive model which integrates a variety of social, climatological, biological, ecological, and environmental factors, among others, that may influence pest and disease progression within a landscape on granular spatial scales (e.g., 1-sq mile). This framework anticipates introduction and development of disease on regional, strategic, and systematic levels in order to combat disease spread and establishment over wide areas. In addition, targeted surveys examine areas near HLB detections outside any existing quarantine boundaries at the time of detection. Targeted sampling strengthens efforts to increase the probability of follow-up HLB detections for effective management aimed at maintaining low disease incidence and suppressing an impending outbreak.

Conducting such guided surveys can greatly aid regulatory agencies in detecting diseases and pests earlier in an epidemic, allowing them to take appropriate mitigation action, and reducing economic and production losses. USDA and CDFA work together to allocate available resources to effectively carry out the risk-based survey for statewide and targeted surveys.

Crucially, the results of these (and other) survey activities are fed back to model developers and researchers associated with DATOC, allowing for a quarterly evaluation of not just disease presence in California, but also spatially explicit citrus variety distribution, disease density and intensity, duration between sample collection and testing, and a multitude of other questions. This has been combined with data from grower liaisons, the CDFA biocontrol program, and the data management program operated by the Citrus Research Board, analysis of which can all be reported back to the Division to inform decision-making.

Scenario analyses: Simulation Modeling

Because there is no "control" situation that can be observed to see how HLB would have developed in California without the presence of the program, it is important that the perspectives obtained from a range of different and independent analyses are triangulated. For example, studies using an Agent-Based Model (ABM) focus on fine detail at relatively small spatial scales (i.e. up to about 25 square miles). The ABM simulates ACP/HLB dynamics in real-world landscapes, with consideration of management programs, social and economic perspectives of growers and residents, and the phase of the epidemic. The model can analyze the performance of any static management program through scenario-based simulations, as well as dynamic programs that react to the developing ACP/HLB situation throughout the simulation. It has been used to investigate management strategies in urban epicenters (LA, Orange), and mixed residential and commercial citrus areas (Riverside, San Bernardino, Ventura).

Results from the ABM can then be triangulated with results from USDA Animal and Plant Health Inspection Service and Cambridge University (UK), who have jointly developed a simulation model for HLB that provides lower resolution outputs that can cover the entire state. By comparison of the different models, together with expert opinion, the program can make decisions backed by the best available projections of possible outcomes. Running scenario-based simulations allows for robust analyses of the effectiveness of control protocols in different citrus landscapes (i.e., residential/urban, commercial, mixed) as the ACP/HLB situation changes, informing the design of efficient, location-based, and sustainable management guidelines at multiple scales.

Concluding remarks

Any program aimed at curtailing the spread of an invasive disease over an area as large and diverse as California will inevitably also be large and complex. The current CPDPD is both of those, but as a consequence of its structure, its incorporation of design principles that have been shown to lead to stable solutions to collective action problems, and its routine use of scientific evidence to support decision making, it is also well-suited to meet its objectives. The program features a large component of self-reflection and reevaluation which ensure that externalities are kept to a minimum while benefits are maximized.

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Research

Collective action in the area-wide management of an invasive plant disease

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ABSTRACT

Area-wide management (AWM) is a strategy for invasive plant pests and diseases in which management actions are coordinated across property boundaries to target the entire pest or pathogen population in an area. Because some people may benefit from the actions of others without bearing the costs, but group-level contributions are required to achieve effective control, AWM suffers from free-riding, yet it has rarely been studied as a collective action problem. To foster collective action for the management of huanglongbing (HLB), California citrus stakeholders have adopted two distinct institutional approaches: Psyllid Management Areas (PMAs), in which coordinated treatments are voluntary, and Pest Control Districts (PCDs), in which coordinated treatments are mandatory. Through a survey distributed to citrus stakeholders in Southern California and a regression analysis of participation levels in AWM over nine seasons, we assess the impact that individual perceptions, institutional approaches and group-level determinants have had on collective action. Our results show that although citrus stakeholders are confident about the benefits of AWM, they are aware of collective action problems and identified the lack of participation as the main barrier to AWM. Group size, grove size and heterogeneity in grove size were found to significantly impact collective action. In addition, our analysis shows that the two institutional approaches that were developed for AWM have followed a different trajectory over time, leading to a discussion of the determinants that may enable and sustain collective action for invasive species management.

Key words: area-wide management; collective action; huanglongbing; invasive species; plant health

INTRODUCTION

In recent years, there has been a growing interest in collective action problems associated with the management of invasive species (Bagavathiannan et al. 2019, Graham et al. 2019, Garcia-Figuera et al. 2021b) which threaten the sustainability of social-ecological systems across the globe (Simberloff et al. 2013, Driscoll et al. 2014, Bebber et al. 2014, Freer-Smith and Webber 2017, Faulkner et al. 2020). Pioneering studies suggested that invasive species management has the characteristics of a weakest-link public good, where the overall level of provision is conditioned by the least effective provider (Perrings et al. 2002). Recent reviews have reinforced the concept of invasive species management as a public goods collective action problem that requires contributions (i.e. adoption of management practices) by affected actors and generates environments free of invasive species that generate mostly non-rivalrous benefits to users (Graham et al. 2019, Niemiec et al. 2020). Conceptualizing invasive species management as a collective action problem creates the potential of applying collective action theories originally deduced from case studies of common-pool resources (Ostrom 1990, Baggio et al. 2016).

Here we use collective action theory to guide analysis of area-wide management of an invasive plant disease, focusing on individual perceptions, institutional approaches and group-level outcomes. *Area-wide management* (AWM), a strategy in which individual actors coordinate their management actions across property boundaries to target the entire pest or pathogen population within an area, is a common recommendation for plant pests and diseases that have high dispersal potential (Vreysen et al. 2007, Hendrichs et al. 2021). Many ecological studies have recommended the implementation of AWM for a broad range of plant pests and diseases (Anco et al. 2019, Laranjeira et al. 2020), yet little attention has been paid to the collective action problem associated with AWM (Kruger 2016, Mankad et al. 2017).

AWM is the main strategy to control huanglongbing (HLB), an invasive disease of citrus trees currently threatening citrus production worldwide (Wang 2019). The most common type of HLB is associated with the bacterium "*Candidatus* Liberibacter asiaticus", which is spread by an insect vector, the Asian citrus psyllid (ACP), *Diaphorina citri* (Bové 2006). The bacterium reproduces in the vascular tissue of citrus trees causing fruit yield and quality loss (Bassanezi et al. 2009). Infected citrus trees eventually die, as commercial varieties are not resistant (Ramadugu et al. 2016) and there is no available cure. Therefore, the main strategy to manage HLB is to prevent trees from getting infected by controlling the insect vector; identifying and removing infected trees; and replacing them with certified plant material (Gottwald 2010). Many studies have shown that these three measures are most effective if they are applied on an area-wide scale (Bassanezi et al. 2013, Singerman et al. 2017, Yuan et al. 2020). However, participation in AWM in HLB-affected regions has been irregular (Singerman and Rogers 2020, Bassanezi et al. 2020).

The collective action problem associated with AWM poses a significant challenge to HLB management, particularly for the area-wide insecticide treatments against the insect vector. Effective vector control requires time-coordinated insecticide sprays by all growers in a sufficiently large area to avoid ACP dispersal, but because coordinated treatments benefit the whole group, any grower may be tempted to rely on others' treatments and avoid the cost of spraying (Singerman and Useche 2019). If a grower fails to coordinate, that property can sustain ACP and spread HLB to the rest (Bassanezi et al. 2013). To face this collective action problem, citrus growers in different regions of the world affected by this disease have developed similar institutional approaches that remarkably follow many of Ostrom's design principles for long-enduring CPR institutions, especially in California (Garcia-Figuera et al. 2021b).

Case study: area-wide management of ACP in California

The current HLB epidemic in California offers an exceptional case study to advance the application of collective action theory to the management of invasive plant pests and diseases. California is the main citrus-producing state in the US, with a $2.3 billion citrus industry that is under threat from HLB (Babcock 2018). The insect vector ACP was first detected in San Diego in 2008 and it quickly became established in Southern California (Bayles et al. 2017). The first HLB-positive tree was found in a residential neighborhood in Los Angeles in 2012 (Kumagai et al. 2013) and since then, more than 2500 HLB-positive citrus trees have been detected and removed from residential properties (CPDPP 2021). No HLB-positive trees have been detected in commercial citrus groves to date. To prevent disease spread to commercial citrus, an AWM program was implemented in Southern California (Imperial, Riverside, San Bernardino, San Diego, Santa Barbara and Ventura Counties). The AWM program consists of two coordinated insecticide treatments for ACP per year, one in the late summer (August - September) and one in the late winter (December - February), but the exact treatment window depends on the county, and some counties conduct additional treatments, particularly in the fall (Grafton-Cardwell 2020). Growers bear the cost of treatments using materials recommended by the University of California (UC ANR 2021). Participation in AWM is considered crucial to avoid the devastating consequences of an HLB epidemic.

In Florida, which used to be the main citrus-producing state in the US, citrus acreage and yield have declined by 38% and 74% since HLB was first detected in 2005 (Graham et al. 2020). An AWM program was implemented, but it failed to achieve collective action (Singerman and Rogers 2020). Scientists and regulatory authorities defined Citrus Health Management Areas (CHMAs) for growers to voluntarily coordinate insecticide treatments for ACP (Rogers 2011), but growers lacked experience in coordinating activities, participation in AWM was not monitored, sanctions were not imposed on noncompliant growers, and there was no state-level industry-led organization coordinating efforts (Garcia-Figuera et al. 2021b). A recent review of the AWM program in Florida recommended replacing this voluntary program with a mandatory component, suggesting:

> "a top-down regulation from the state to the packinghouses and processors, requiring them to provide documentation that their fruit has been subject to coordinated sprays. These companies would, in turn, require such documentation to growers as part of their specifications for purchasing their fruit. In this way, growers would need to organize themselves locally to fulfill such a requirement, perhaps through their associations, and be assessed charges (from a third party) for the sprays on a per-acre basis"

-(Singerman and Rogers 2020).

California offers an alternative example of an AWM program for ACP that combines voluntary and mandatory components as part of a *bottom-up*, grower-led strategy to achieve collective action. To overcome the collective action problem associated with AWM and coordinate insecticide treatments for ACP, California citrus growers have adopted two distinct institutional approaches: Psyllid Management Areas (PMAs) and Pest Control Districts (PCDs).

PMAs are groups of approximately 20 neighboring growers who voluntarily coordinate insecticide treatments for ACP over a 2-3 week window. PMAs were established by the Citrus Pest and Disease Prevention Program (CPDPP) as relatively small zones that share a landscape, similar environmental conditions, and most importantly a social network of growers (Grafton-Cardwell et al. 2015). Some PMAs have a voluntary leader who is responsible for contacting the rest of the growers when it is time to spray, following instructions from their grower liaisons. In other PMAs, growers are contacted directly by grower liaisons who were hired by CPDPP to coordinate the network of PMAs in a region, facilitate area-wide treatments, disseminate outreach and education materials and act as knowledge brokers between the state-level CPDPP, the regional ACP/HLB Task Forces and the growers. ACP/HLB Task Forces are voluntary groups of growers, county authorities and other citrus stakeholders that operate at a county or larger scale with the aim of coordinating efforts among PMAs. In regions that rely on PMAs to coordinate treatments, Task Forces meet every 1-3 months and recommend AWM treatments based on the number of ACP adults observed on yellow sticky traps.

PCDs are special districts instated by local growers to have the legal authority to control, eradicate, or respond to the effects of pests and diseases affecting a specific crop (UCCE 2005). Citrus PCDs currently exist in Southern California in Imperial, Riverside and San Diego Counties. Some PCDs were set up to control other citrus pests before ACP and HLB were detected. In other cases, PCDs were newly created for ACP and HLB (Appendix 3, Table A3.1). Within a county, PCDs are established by majority vote of growers in the proposed district (≥51% by area), who become subject to the rules established by the PCD board of directors. Inside a PCD, treatments against a specific pest can be mandatory. If a grower does not comply, the California Food and Agricultural Code allows the PCD to treat the non-compliant property and send a bill to the owner. If the bill is not paid within a certain time, the County has the authority to sell that property to recoup the cost of the treatment (FAC 1988). PCDs are responsible for indicating the timing of the area-wide ACP treatments in conjunction with the grower liaisons. PCDs are typically funded by per-acre grower assessments. Some PCDs (Coachella, Hemet and San Diego) incentivize coordination by providing a complete or partial reimbursement of grower assessments if they show proof of compliance with the AWM treatment within the recommended window.

As the HLB epidemic progresses in Southern California, the main objectives of this study were to assess citrus stakeholders' perceptions of the collective action problem associated with AWM and to quantify the impact of institutional approaches and group-level determinants on collective action. To achieve this, we combined two unique sources of information, a survey distributed to 300 citrus stakeholders during a series of grower meetings that provided context about the individual perceptions of AWM as a collective action problem, and the historic record of group-level participation in AWM from 94 management units in Southern California over nine seasons. Combining these two data sources we disentangle the interactions between individual perceptions, group-level determinants and institutional approaches that may impact collective action in provision of AWM of ACP in California. Lessons learned can apply to other invasive plant pests and diseases.

METHODS

Research Design

This study uses survey data to measure individual grower perceptions of AWM, and group-level participation data in AWM across PCDs and PMAs in Southern California. We first describe the survey that was used to assess citrus growers' confidence in the benefits of AWM, the main barriers to AWM and their confidence that their neighbors will participate. This information is intended to provide individual-level context to the analysis of participation in PMAs and PCDs, and to show how perceptions have evolved since the AWM program was implemented. We then describe the statistical model used to analyze AWM participation in Southern California. The unit of analysis is the AWM unit (PMA or PCD). The dependent variable in the model is the level of participation in AWM. Independent variables include the institutional approach (PMA or PCD), group size, size of the resource system, size of citrus groves, heterogeneity in grove size, season of treatment and age of program, as explained below.

Survey

Survey design

The questionnaire to assess the citrus stakeholders' perception of the AWM program was designed by the researchers as part of a broader study to assess citrus stakeholders' propensity to adopt HLB management practices in California (Garcia-Figuera et al. 2021a). The questionnaire is provided in Appendix 1.

The most relevant questions for our study focus on grower perceptions of AWM and collective action variables. To assess the citrus stakeholders' perception of their group efficacy (Niemiec et al. 2016, Lubeck et al. 2019) or response efficacy (Mankad and Loechel 2020), we asked them how likely they thought it was that coordinated treatments against ACP would slow down the spread of HLB more than uncoordinated treatments. The answers to this question were a 5-point Likert scale of *very* unlikely, *unlikely*, *maybe*, *likely* or *very likely*. This question was in line with a previous question asked in a similar survey in 2015 (Milne et al. 2018).

To gain insight into the citrus stakeholders' perception of the main barriers to AWM, and to determine if they perceived it as a collective action problem, we asked participants to indicate what they thought was the main barrier to area-wide management of ACP in their area, choosing among *preference to spray in one's own timing*, *access to sprayers*, *cost*, *getting everyone to* participate or *worry about integrated pest management (IPM) disruption*. These options were based on interactions with the CPDPP and conversations with grower liaisons, a previous survey done by our group and collaborators in 2015 (Milne et al. 2018), and a study with citrus growers in Florida, which found that the main reason why growers did not participate in the AWM program was that *neighbors do not participate*, followed by *I prefer to spray on my own timing* (Singerman et al. 2017).

To measure stakeholders' confidence that others around them were contributing to collective effort, we asked them how likely they thought it was that their neighbors would apply insecticides for ACP within recommended treatment windows, choosing among *very unlikely*, *unlikely*, *maybe*, *likely* and *very likely.* This question addressed the importance of trust for collective action, and it was based on similar studies of collective weed control efforts (Lubeck et al. 2019), collective insect pest management (Stallman and James 2017) and groundwater management (Niles and Hammond Wagner 2019). We specifically asked this question after asking about the main barrier to AWM to prevent bias in responses to the question about barriers that could potentially arise once participants were asked about their neighbors.

To contextualize the three questions about AWM within the broader HLB control program in California, we asked participants about their self-reported intention to stay informed and communicate with the grower liaisons; their self-reported intention to communicate with neighbors (growers and homeowners); and their perceived vulnerability to HLB (how likely they thought it was that an HLB-positive tree would be detected in their grove in the next year). These questions were also assessed on a 5-point scale of *very unlikely*, *unlikely*, *maybe*, *likely* and *very likely*. Our expectation is that the intention to stay informed and communicate with grower liaisons would be positively correlated with trust in the efficacy of AWM, as it has been the main strategy promoted by the CPDPP for years (Grafton-Cardwell 2020). We expect the intention to communicate with neighbors to be positively correlated with trust in neighbors, as previous studies have shown that face-to-face communication is essential to develop trust and reciprocity that may facilitate collective efforts in plant pest and disease management (Maclean et al. 2019, Sherman et al. 2019). Finally, we test for possible relationships between perceived vulnerability to HLB and perceived efficacy of AWM and between vulnerability and trust in neighbors.

Controls for operator and operation demographics are based on previous agricultural surveys, including surveys about HLB (Stallman and James 2015, Singerman et al. 2017, Milne et al. 2018, Mankad et al. 2019). The research protocol was submitted to the Institutional Review Board (IRB) at UC Davis [1436590-1] and it was granted “Exempt” status because it entailed low risk to participants

Survey distribution

The survey was distributed at three grower meetings that were part of the Citrus Growers Educational Seminar Series, organized by the Citrus Research Board (CRB) in collaboration with the University of California Cooperative Extension (UCCE) in June of 2019 in Palm Desert (southeast California), Santa Paula (coastal California) and Exeter (San Joaquin Valley). These are annual seminars organized by the CRB and UCCE, for which attendees get Continuing Education units & Certified Crop Adviser hours. The availability of these credits tends to result in a larger than usual attendance at grower workshops, reducing selection bias that could arise from sampling growers with more narrow interests. Selection bias was further limited by the fact that the annual election of citrus industry representatives for the CRB was scheduled on the day of the seminars in Palm Desert and Exeter. Nevertheless, as with most agricultural surveys, there likely remains some response bias towards more involved and larger growers, which limits the generalizability of our findings to the fringe of more disconnected, smaller growers.

To maximize participation, growers completed surveys during a designated time immediately after a presentation of best management practices for HLB (Garcia-Figuera et al. 2021a). The survey was introduced to participants as voluntary and anonymous, in compliance with IRB regulations. It was presented with the TurningPoint add-in for Microsoft PowerPoint (Microsoft, Redmond, WA, U. S. A.), and responses were collected using clicker handsets from TurningPoint (Turning Technologies, Youngstown, OH, U. S. A.) that had been given to each participant before the seminar started. Participants were given about one minute to answer each question. Once the polling time was closed for each question, a summary of the responses (percentage of participants that had chosen each response) was shown to the audience and briefly discussed before moving to the next question.

Analysis of participation in AWM

Dependent Variable: participation in AWM

A regression model was used to quantify the impact of the institutional approach and group-level determinants on participation in AWM. The unit of analysis was the AWM unit (PMA or PCD). The dependent variable was the level of participation in AWM, measured as the percentage of the citrus acreage within each management unit treated within the designated treatment window. As mentioned, the grower liaisons and CDFA have been tracking participation in AWM since coordinated treatments for ACP started to be recommended in Southern California in 2015 (Grafton-Cardwell et al. 2015). The Task Forces directing the PMAs or the board of directors of the PCDs determine the most appropriate window for treatment, and the grower liaisons collect the Pesticide Use Reports (PURs) submitted to the County Agricultural Commissioners (CACs) to determine the number of acres that were treated within the recommended window. Participation levels are then calculated as the percentage of the total citrus acreage within each management unit that was treated within the recommended window. These percentages are reported to CDFA in order to determine which management units qualify for residential buffer treatments (CDFA 2020).

This unique data set of participation levels covers a total of 94 active AWM units in Southern California: 16 operating as part of a PCD and 78 operating as PMAs (Fig. 1). Although there are some areas within some of the counties with PCDs that are organizing AWM treatments voluntarily, participation in those treatments is not currently recorded. Thus Southern California counties are either operating through PCDs or PMAs. Imperial County has a PCD with 7 growing zones; Riverside County has two PCDs (Hemet and Coachella) with a total of 6 growing zones; San Bernardino County has 19 active PMAs; San Diego County has a PCD with 3 areas; Santa Barbara County has 9 active PMAs; and Ventura County has 50 active PMAs. Participation levels from these management units were available for nine seasons: the Fall of 2016, the Winter of 2016-2017, the Fall of 2017, the Winter of 2017-2018, the Fall of 2018, the Winter of 2018-2019, the Fall of 2019, the Winter of 2019-2020 and the Fall of 2020 (Fig. A3.1 in Appendix 3). In total, the data set contained 840 observations corresponding to participation levels in 94 AWM units over nine seasons.

Independent Variables

Independent variables that could impact participation in AWM were selected from recent studies related to collective action and invasive species management (Lubeck et al. 2019, Graham et al. 2019, Mankad and Loechel 2020), as well as information gathered through years of interaction with the grower liaisons and the CPDPP (McRoberts et al. 2019). Seven independent variables were considered:

1. *Institutional approach*: PMA (baseline) or PCD.
2. *Group Size* of each PMA or PCD, measured as the number of different pesticide use permits in each management unit, based on the information recorded in the database of citrus operations in California maintained by the CRB (Appendix 2)
3. *Size of the resource system*, *i.e.*, total citrus acreage under each management unit, based on the information in the CRB citrus database (Appendix 2).
4. *Size of citrus groves,* measured as the average grove size in each management unit, based on the information in the CRB citrus database (Appendix 2).
5. *Heterogeneity in grove size*, measured in terms of the standard deviation of the size of citrus groves in each management unit, based on the information in the CRB citrus database (Appendix 2).
6. *Season of Treatment*: fall (baseline) or winter.
7. *Age of Program, i.e.,* consecutive season (1-9), from 2016 to 2020.

Hypotheses

Collective action theory and previous studies on the collective management of invasive species and HLB guided our hypotheses about the impact of institutional approaches and group-level determinants on participation in AWM (see Table 1).

1. *Institutional approach*. We hypothesize that PCDs have higher participation levels than PMAs (baseline), all other factors being equal, because PMAs are voluntary and require a lower degree of commitment, while PCDs are mandatory and require contributions on a per-acre basis.
2. *Group Size* of each PMA or PCD. Based on the collective action literature, we hypothesize that management units with fewer members have higher participation levels, because fewer people need to agree to treat in coordination, and transaction costs of coordination are lower (Ostrom 2009).
3. *Size of the resource system*. We hypothesize that the size of the management unit has a negative effect on participation. As the citrus acreage under a PMA or PCD increases, there is a

higher chance that part of that acreage will not be treated within the recommended window, and the cost of defining boundaries, monitoring participation and gaining ecological knowledge about the status of the ACP infestation may be higher (Ostrom 2009). However, from an ecological perspective, the bigger the PMA or PCD, the more effective the coordinated treatments against ACP will be, because the insect will not be able to disperse to nearby untreated groves (Rogers et al. 2010, Flores-Sánchez et al. 2017).

4. *Size of citrus groves.* We hypothesize that PMAs or PCDs with larger groves have higher participation levels, because larger operations may have more resources to fund treatments and owners may be more invested in citrus production (Mankad et al. 2019).

5. *Heterogeneity in grove size*. We hypothesize that management units with a higher standard deviation of the size of citrus groves would have lower participation levels than units with more similarly sized groves, as heterogeneity (*i.e.*, thinking that the neighbors' farms or properties were different) was found to negatively impact collective action for pest management (Stallman and James 2017).

6. *Season of Treatment*. We hypothesize that fall treatments would have higher participation than winter treatments, because entomologists have strongly emphasized the importance of fall treatments to reduce ACP populations, which tend to peak at the end of the summer or the beginning of fall in California (Grafton-Cardwell 2020). Winter treatments are mostly preventive, aimed at targeting ACP adults that may have survived through the coldest months of the year before the spring flush (*i. e.*, young leaf growth).

7. *Age of Program.* Our hypothesis was that we would not see a systematic change in participation over the age of the program, from the initial treatment season in 2016 to 2020. However, we were interested in testing if there had been an increase or decrease in participation over time after controlling for other factors, which would be indicated by a positive or negative regression coefficient, respectively. In addition, we tested if there was an interaction between the institutional approach and the age of the program, which would suggest that the evolution of participation has followed a different trajectory over time in PCDs and PMAs.

Analytical approach: zero-and-one-inflated beta regression model

Because participation in the AWM program in California is measured as a proportion of the citrus acreage within each management unit that was treated in coordination, it is a continuous variable that falls within the closed interval [0,1]. The dataset contains 11 observations at 0 (all PMAs), 668 observations in the interval (0,1) and 161 observations at 1 (60 PCDs and 101 PMAs). Given these characteristics, we chose to use a zero-and-one-inflated beta (zoib) regression model implemented through the R package “zoib” (Liu and Kong 2015). More information about the analytical approach can be found in Appendix 2.

RESULTS

Descriptive statistics of survey participants

In total, we collected responses from 300 participants (Garcia-Figuera et al. 2021a), but for this study we focused on the responses to the questions mentioned in the previous section from 98 individuals who indicated that they had groves in the Southern California counties that are routinely conducting AWM treatments (Imperial, Riverside, San Bernardino, San Diego, Santa Barbara and Ventura). The socio-economic characteristics of these survey participants are shown on Table A3.2 in Appendix 3.

Although the survey was based on a non-random sample of attendees at citrus stakeholder meetings, we believe that it was reasonably representative of citrus production in Southern California. Most participants were from Ventura County (53), followed by Riverside (14), Santa Barbara and Ventura (7), Riverside and San Diego (5), Santa Barbara (4), Imperial (2) and other combinations (13). To give an idea of the size of the industry in these counties, there are about 874 operations with bearing or non-bearing citrus trees in Ventura County, 590 in Riverside, 152 in Santa Barbara, 1254 in San Diego, 20 in Imperial County and 271 in San Bernardino (USDA-NASS 2019). Total citrus acreage in 2018 was 18,447 acres in Ventura (Ventura CAC 2019), 17,333 in Riverside (Riverside CAC 2019), 1291 in Santa Barbara (Santa Barbara CAC 2019), 11,701 in San Diego (San Diego CAC 2019), 9231 in Imperial (Imperial CAC 2019) and 2435 in San Bernardino (San Bernardino CAC 2019).

Most of the survey respondents from these counties were *grove owners* (38), *PCAs* (18) or *ranch* managers (17). Although 18 self-identified as *other*, we did not detect any significant evidence of differences in the distribution of responses to the relevant questions in the survey among different types of stakeholders, so all of them were considered as a single sample for analyses and are referred to as “participants" or “respondents”. In terms of grove size, there was an under-representation of small citrus groves in our sample (23%) compared with state-wide percentages (50%); and an over-representation of large groves (29% vs. 1%) (USDA-NASS 2019). In terms of age, the sample was representative, with 52% of respondents between the ages of 35 and 64, compared with 55% of growers between those ages in their counties of origin (USDA-NASS 2019). Younger growers were slightly over-represented. Organic citrus production was also over-represented in the survey, as 8% of citrus operations and 3% of acreage in the state of California are estimated to be certified organic (USDA-NASS 2017, 2019), yet 13% of participants indicated that they grew citrus organically. Participants for whom citrus production represented less than a quarter of their income comprised 41% of the sample, compared with participants who depended on citrus for their livelihood (23%).

Individual-level perceptions of collective action in area-wide management

The majority of survey participants (87%) thought that it was *likely* or *very likely* that coordinated insecticide treatments for ACP would slow down HLB spread more than uncoordinated treatments, revealing a strong confidence in the benefits of collective action (Fig. 2). Participants with different socio-economic backgrounds did not provide significantly different answers to this question, and confidence in AWM was consistent across different counties and institutional approaches. Since participants were not asked specifically about the institutional approach that they were using for AWM, but about the county/ies where they grew citrus, counties that coordinate AWM exclusively through PCDs (Imperial) were grouped under the "PCD" category; counties that are coordinating AWM exclusively through PMAs (San Bernardino, Santa Barbara, Ventura and combinations of these) were grouped under the "PMA" category, and the rest were grouped under "Both".

When participants were asked to identify the main barrier to AWM in their area, the majority thought that it was *getting everyone to participate* (64%). Therefore, although most participants believe that AWM is beneficial, they are worried that others might not contribute, a clear evidence that there is a collective action problem. About a fifth thought that the main barrier was *cost* (19%), and a few thought that it was *worry about IPM disruption* (6%), *access to sprayers* (5%) or *preference to spray in their own timing* (5%) (Fig. 2). The participants' role in citrus production, their age, their citrus acreage or how much of their income came from citrus did not change these perceptions of the main barriers to AWM. However, respondents who grew citrus organically were significantly more worried about possible disruptions to their IPM program caused by repeated insecticide sprays than conventional producers, or those who grew citrus under both systems. Interestingly, we did not detect a significant difference in the barrier identified between participants that coordinated AWM through PCDs, PMAs or both (P=0.22 on the Kruskal-Wallis test).

Subsequently, participants were asked how likely they thought it was that their grower neighbors would apply insecticides for ACP within recommended treatment windows, which is a way of assessing their trust in neighbors. More than half (54%) thought that it was *likely* or *very likely*; about a fifth (21%) chose *maybe*; and a quarter (24%) thought that it was *unlikely* or *very unlikely* (Fig. 2). This reveals that many participants trust their grower neighbors to coordinate, but there is a certain degree of what has been called "strategic uncertainty", or uncertainty about the actions and beliefs of others. This was one of the main barriers for AWM of ACP in Florida

(Singerman and Useche 2019). Participants' trust in neighbors did not significantly vary with their role in citrus production, their age, their management system or their income dependency on citrus. Nevertheless, a significantly higher proportion of small growers (those with less than 5 acres of citrus) thought that it was *unlikely* or *very unlikely* that their neighbors would coordinate. Despite differences in AWM participation across Southern California, there was no evidence of differences in terms of participants' trust in neighbors among counties (P=0.19) or institutional approaches (P=0.68).

Among participants who thought that the main barrier to AWM was *getting everyone to participate*, a third (33%) thought that it was *likely* or *very likely* that their neighbors would apply insecticides within designated treatment windows, while more than a quarter (14%) chose *maybe*. Therefore, some participants seem to be concerned about people other than their grower neighbors. In other citrus-growing regions affected by HLB, residential neighbors with backyard citrus trees have been a major concern for citrus growers (Johnson and Bassanezi 2016, Sétamou 2020).

As expected, collective action was positively impacted by communication. Participants who were more likely to stay informed and communicate with the grower liaisons were also more likely to believe in the efficacy of AWM (ρ= 0.21, P=0.045, Fig. A3.2). Therefore, engagement with the CPDPP may promote confidence in the efficacy of AWM, suggesting an avenue for outreach. Although we did not detect a significant positive correlation between the self-reported propensity to communicate with neighbors and trust in the neighbors' ability to coordinate (ρ= 0.18, P=0.077, Fig. A3.3), the lack of significance might be due to the fact that the question about communication referred to both grower neighbors and homeowner neighbors. Overall, participants who indicated that they were more likely to communicate with their neighbors tended to think that it was more likely that their neighbors would conduct coordinated insecticide treatments within recommended windows, suggesting that communication might be important to develop trust in others' contributions to achieve collective efforts. The participants' perceived vulnerability to HLB and their confidence in the benefits of AWM, or vulnerability and confidence in neighbors, were not correlated.

Finally, to provide historic context to the survey, we compared it to an equivalent survey that was conducted in 2015, when the AWM program was getting started in California (Milne et al. 2018). At that time, participants were asked "to rate the effectiveness of area-wide control of ACP". Some participants from Southern California thought it provided *excellent control* (17%), most thought that it provided *moderate control* (65%), and some (18%) considered it to be of *little effect* or *not effective* (Milne et al. 2018). Compared with our results, where 87% of participants thought that AWM was beneficial, confidence in AWM seems to have increased over time. In 2015, the majority of respondents from Southern California indicated that *participation* was among their biggest concerns about AWM (54%), followed by *cost* (39%), *number of sprays* (26%), *pesticide* resistance (19%), *IPM program* (22%), *options for organic* (17%) and *access to sprayers* (11%) (Milne et al. 2018). Therefore, the two main concerns that were identified in 2015, participation and cost, were still the main barriers identified in 2019, with participation being the major concern by an ample majority in both surveys.

Group-level determinants of collective action in area-wide management

A zoib regression model was used to quantify the impact of several group-level variables on collective action in AWM. The model with credibility intervals that did not include 0 for any of the independent variables and generated the lowest DIC included the institutional approach (PMA/PCD), the group size, the size of the resource system, the size of the citrus groves in the unit, the heterogeneity in grove size, the season of treatment (Fall/Winter), the age of the program (1-9), an interaction term between the institutional approach and the age of the program, and an interaction term between the size of the citrus groves and the heterogeneity in grove size (Table 2). Other fitted models are shown on Tables A3.3-5 in Appendix 3.

In the selected zoib model, the signs of the coefficients of the independent variables were mostly as hypothesized (Table 1). Our first hypothesis was that mandatory PCDs would have higher participation than voluntary PMAs. The coefficient of the institutional approach was negative (Table 2), which may seem to contradict our hypothesis. However, we detected a significant interaction between the institutional approach and the age of the program, which means that the effect of the type of institution on participation depends on time, and cannot be interpreted in isolation (Brambor et al. 2006). The positive sign of the interaction term suggested that participation had been growing over time in PCDs, while it had been declining over time in PMAs. To illustrate the institutional differences, Figure 4 displays predicted levels of participation over time and in different seasons based on the type of institution, while fixing all other variables at their mean value. The predicted values clearly show an upward trajectory of participation in PCDs with a downward trajectory over time in PMAs. Even though PCDs started with lower participation levels, participation has been growing over time in this institution, while it has been declining in PMAs (Fig. 3).

As shown on Fig. 3, the season when the AWM treatments are conducted also has an effect on participation. As hypothesized, winter treatments were found to have 0.84 times the odds of having higher participation than fall treatments (Table 2). Therefore, all other variables being equal, winter treatments tended to have slightly lower participation than fall treatments. This may have implications for vector and disease control, since insecticide treatments during the winter dormant period, before the spring flush, were found to be crucial for ACP control in Florida (Qureshi and Stansly 2010) and Texas (Sétamou 2020).

In line with the collective action literature, the model estimated that group size (*i.e.*, the number of pesticide use permits in the AWM unit) had a negative effect on the mean of the beta distribution, the dispersion parameter of the beta distribution, the probability of having none of the citrus acreage treated within the window and the probability of having all of the citrus acreage treated within the window. To illustrate how these effects would impact participation in AWM, the model was used to predict participation for a fall treatment during season number 9 based on the group size, while fixing all other variables at their mean value. Under these conditions, the model predicted that participation in a mandatory PCD would drop from 86% with 10 members to 82% with 30 members, and in a voluntary PMA it would drop from 79% with 10 members to 74% with 30 members. Interestingly, the model suggested that the optimum number of members to maximize participation in a PMA would be around 5 for an average PMA size, average grove size and average heterogeneity in grove size (Fig. 4).

The size of the resource system (*i.e.*, the total citrus acreage treated in the management unit) was not a limiting factor in this case. As shown on Table 2, the coefficient of the size of the resource system was estimated to be zero, so once the size of the group and other variables were considered, the size of the resource system by itself did not impact the level of participation in AWM.

As hypothesized, the model showed that the average size of citrus groves and the heterogeneity in grove size had an impact on participation (Table 2). More importantly, these factors interacted, so the effect of heterogeneity on participation depended on the size of citrus groves, and vice versa. As shown on Fig. 5, when the groves were mostly small (with an average size of 2 acres), the presence of a few large groves could have a beneficial effect on participation, but if the groves were mostly large (with an average size of 50 acres), participation could decline very sharply in the presence of a few small groves. This suggests that large growers might be acting as opinion leaders in areas predominated by smaller groves, helping promote collective action; while in areas predominated by large groves, a few small operations that might be owned by hobbyists or less engaged growers could lead to a dramatic drop in participation, a clear evidence of a weakest-link collective action problem.

DISCUSSION

Citrus stakeholders in Southern California are aware of the collective action problem associated with HLB management. Our survey showed that there was a high level of confidence in the benefits of coordinated insecticide treatments for HLB management, but also a widespread opinion that getting everyone to participate is the main barrier to successful AWM, and some worry that neighbors may not contribute to the collective effort. The high level of agreement about the benefits of AWM may predispose citrus stakeholders to achieve collective action, as collective responses were found to be enhanced when stakeholders acknowledged the cross-boundary nature of invasive species management and were aware of the benefits associated with collective action (Graham et al. 2019). In the context of collective weed control, awareness of cross-boundary interrelationships or confidence that collective efforts can achieve desired outcomes were also found to influence engagement (Lubeck et al. 2019).

Although only a quarter of the survey participants believed that it was *unlikely* or *very unlikely* that their neighbors would coordinate, this level of mistrust could jeopardize collective action if efforts are not made to promote engagement with the state-wide HLB control program and to encourage communication between neighbors. In a previous study about the management of an invasive tree in Hawaii, people felt discouraged about controlling it because they perceived a lack of participation or coordination among neighboring landowners (Niemiec et al. 2016). In another study with crop farmers in Missouri, the perceived trustworthiness of their neighbors did not affect their willingness to participate in cooperative pest control (Stallman and James 2015), but farmers whose farms were dissimilar from their neighbors' were significantly more willing to cooperate if they trusted them, suggesting that trust may be important to face heterogeneity (Stallman and James 2017). Although we did not detect a significant correlation between communication with neighbors and trust in neighbors, there was a positive trend, in line with previous studies that showed that face-to-face communication is essential to develop trust and reciprocity in collective efforts for pest and disease management (Maclean et al. 2019, Sherman et al. 2019).

Mistrust in neighboring growers was found to be an important factor behind the failure of the AWM program for HLB in Florida. An experimental voluntary contribution game conducted with Florida citrus growers in 2016 showed that the most limiting factors for participation in AWM were the threshold required for collective action to have a successful outcome, the beliefs about others not coordinating, and risk aversion (Singerman and Useche 2019). When the threshold for coordination in the game was high, growers chose to coordinate less as the group size increased. However, once they were shown an empirical study that proved that participation in AWM was beneficial, 30% of the growers chose to coordinate more (Singerman and Useche 2019). The authors concluded that future studies that clarified what participation thresholds would be required for successful HLB management could increase the success of collective efforts (Singerman and Useche 2019), but those studies remain to be conducted.

Compared with Florida, California offers an alternative example of an AWM program for ACP that combines voluntary and mandatory institutions to achieve collective action. Although there are precedents of successful AWM programs for other plant pests and diseases in the state (Haviland et al. 2021, Simmons et al. 2021), the level of mobilization that ACP and HLB have imposed on citrus growers is extraordinary, and justified by the devastating consequences of the HLB epidemic in Florida and other citrus-growing areas (Graham et al. 2020, Bassanezi et al. 2020). Soon after ACP and HLB were detected in California, citrus growers partnered with CDFA to establish the CPDPP and organized themselves in PMAs, or took advantage of existing PCDs, expanded them, or even created new PCDs to coordinate insecticide treatments for ACP and suppress the insect population, in an attempt to limit the spread of HLB. The key difference between PMAs and PCDs is that treatments are voluntary in PMAs while they are mandatory in PCDs, and this difference appears to have had profound consequences for participation. Although PCDs had lower participation levels in the beginning of the AWM program, maybe reflecting that in some counties they were created precisely to avoid free-riding, our analysis shows that PCDs have been growing in participation over time while participation has been declining in PMAs, all other variables being constant. This raises the question of whether a voluntary institutional approach will be able to sustain collective action for ACP management in California in the long term.

The other group-level determinants considered in our regression analysis may shed some light in this respect. In line with collective action theory, the size of the group was found to be a limiting factor for AWM. This finding agrees with case studies of CPRs, in which the number of social-ecological system users was one of the key factors that determined self-organized collective action (Ostrom 2009), and it was also one of the most commonly cited factors for collective action in invasive species management (Graham et al. 2019). As there are higher transaction costs associated with organizing larger groups and the probability of free-riding is higher (Graham et al. 2019), we expected participation in AWM to go down as the number of people who needed to coordinate treatments increased, as observed. This was one of the reasons why PMAs were designed on the basis of social criteria, so that they would comprise relatively small groups of growers that were part of the same social network (Grafton-Cardwell et al. 2015). In Florida, the AWM units for ACP were designed to comprise a sufficiently large area to achieve ACP control (Rogers 2011), and similar epidemiological criteria were followed in Mexico (SENASICA 2012). From a collective action perspective, the total size of the resource system was found to have no effect on participation once the institutional approach, the group size, the size of citrus groves and other variables were considered.

Most importantly, we detected a positive effect of heterogeneity in grove size when the majority of citrus groves in the AWM unit were small, and a negative effect when the majority of citrus groves were big. This suggests that the collective action problem associated with AWM might be more difficult to overcome when there is a large mass of big commercial growers and a few small growers who might not have the resources or interest in coordinating insecticide treatments for ACP. This result aligns with years of discussions at CPDPP meetings about the risk of these small growers being the weakest link in the collective action problem. Properties with 25 citrus trees or more are considered to be commercial citrus groves in California, but many of them are residential properties whose owners may not be willing to spend resources to care for their citrus trees. These property owners rarely participate in citrus grower meetings such as those where we conducted our survey, and it has been difficult to motivate them to participate in AWM. In our survey sample, small growers (less than 5 acres of citrus) were less likely to trust their neighbors than big growers, probably suggesting a higher prevalence of weakest links in communities predominated by smaller groves. Considering that around 34% of the citrus groves in Southern California that are routinely conducting AWM treatments have less than 5 acres (USDA-NASS 2019), heterogeneity may not have had a negative impact to date, but it could become relevant in parts of California predominated by big groves intermixed with a few smaller operations, such as the Central Valley.

Apart from the variables captured in the regression model, it may be important to consider that the lack of sufficient equipment to conduct all the insecticide treatments at the same time has been a limiting factor for participation in some areas of Southern California. Unfavorable weather events (strong winds, mud slides, wildfires) have also had a negative impact on participation, and may explain some of the 0 participation values recorded for some PMAs. The allocation of water to apply some of the systemic treatments through the irrigation system has also been a limiting factor, particularly in San Bernardino County. Finally, the lower participation detected for winter treatments compared to fall treatments could be a target for outreach from the CPDPP, as it may be related to the lower adoption of preventive treatments compared with suppressive treatments, which has been observed before in other plant diseases (Hillis et al. 2017).

As ACP and HLB continue to spread in Southern California, it is likely that an HLB-positive tree will be detected in a commercial grove in the near future. Participation in AWM will then become more crucial to keep the ACP populations under control and limit disease spread. Although our results suggest that citrus stakeholders are aware of the benefits of coordinated insecticide sprays for ACP, more research will be needed to determine the specific benefits and costs of area-wide management; to estimate the participation threshold required for effective control under different ecological and social conditions; to evaluate the impact that this information may have on the growers' intentions to coordinate efforts; and to determine how individual intentions will translate into group-level outcomes. For the type of "co-managed" collective action adopted in California, where private landowners entered in a cooperative arrangement with an external organization (CDFA) to promote collective action, previous studies have shown that fostering community-building activities and learning opportunities that build trust among participants, highlighting participants' positive experiences and employing multiple forms of incentives can help sustain collective action (Graham et al. 2019). The growing interest in addressing invasive species management as a collective action problem will likely lead to additional studies in other social-ecological systems that will enhance our understanding of the factors and strategies that might sustain collective action in area-wide management.

CONCLUSION

In this study, we provide evidence of how individual perceptions and group-level variables may impact collective action in the area-wide management of an invasive plant disease. We contribute to the emergent application of collective action theory to invasive species management by showing that confidence in the benefits of the collective effort, trust in neighbors' contributions, the size of the group, the size of the properties and the heterogeneity in property size may be key factors to consider when designing an area-wide management program for an invasive plant pest or disease. In addition, we show that voluntary vs. mandatory institutional approaches may lead to distinct collective outcomes over time. Further studies in different social-ecological systems that clarify the benefits of collective action and combine surveys with quantitative analyses of collective outcomes will likely improve our understanding of the social dimensions of biological invasions, helping societies to better face the threat of invasive species.

Data Availability

The data sets and R code that support the findings of this study will be openly available in a Github repository at https://github.com/nmcr01?tab=repositories upon publication of this article.

Ethical approval for this research study was granted by the Institutional Review Board at the University of California, Davis.

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Table 1. Independent variables and hypotheses in the AWM participation regression model

Independent variable	Type of variable	Expected sign
Institutional approach	Categorical: PMA (baseline)/PCD	Positive
Group size	Numeric (min 1, median 10, max 65)	Negative
Size of the resource system	Numeric (min 11 acres, median 404 acres, max 3652 acres)	Negative
Size of citrus groves	Numeric (min 0.6 acres, median 9 acres, max 30 acres)	Positive
Heterogeneity in grove size	Numeric (min 2 acres, median 9 acres, max 99 acres)	Negative
Season of treatment	Categorical: Fall (baseline)/Winter	Negative
Age of program	Numeric (1-9)	?

Table 2. Posterior mean, 95% credible interval and potential scale reduction factors (psrf) for the parameters in the selected zoib regression model.

Model component	Parameter	Posterior mean	2.5% quantile	97.5% quantile	Point estimate of psrf	Upper CI of psrf
logit(mean)	Institutional approach (PMA/PCD)	-1.093	-1.653	-0.571	1.00	1.03
	Group size	-0.011	-0.016	-0.005	1.02	1.09
	Size of the resource system	0.000	0.000	0.001	1.00	1.02
	Size of citrus groves	0.104	0.064	0.141	1.00	1.01
	Heterogeneity in grove size	0.083	0.048	0.121	0.99	0.99
	Season of treatment (Fall/Winter)	-0.169	-0.298	-0.046	1.01	1.01
	Age of program	-0.074	-0.100	-0.048	1.00	1.00
	Institutional approach x Age of program	0.174	0.100	0.255	1.01	1.07
	Size of citrus groves x Heterogeneity in grove size	-0.006	-0.008	-0.004	1.00	1.02
	Intercept	0.426	0.108	0.792	0.99	1.00
log(dispersion)	Institutional approach (PMA/PCD)	-0.808	-1.305	-0.378	1.01	1.01
	Group size	0.034	0.024	0.043	1.01	1.06
	Size of the resource system	0.000	0.000	0.001	1.00	1.04
	Size of citrus groves	0.063	0.025	0.100	1.02	1.09
	Heterogeneity in grove size	-0.053	-0.083	-0.018	1.03	1.14
	Intercept	0.879	0.624	1.134	1.00	1.00
logit(Pr(y=0))	Institutional approach (PMA/PCD)	-67.449	-188.903	-4.659	1.01	1.06
	Group size	-0.580	-0.934	-0.302	1.00	1.00
	Intercept	-1.426	-2.380	-0.506	1.00	1.02
logit(Pr(y=1))	Group size	-0.319	-0.377	-0.266	1.00	1.03
	Heterogeneity in grove size	0.034	0.002	0.065	1.00	1.01
	Intercept	0.541	0.103	1.035	1.00	1.01

(con'd)

Observations	840
DIC	1679849
psrf	1.1

Fig. 1. Geographical location of Psyllid Management Areas (PMAs) and Pest Control Districts (PCDs) for area-wide management (AWM) of the Asian citrus psyllid (ACP) in Southern California. The outline of PMAs is shown in blue and the outline of PCDs is shown in purple. Each PMA and PCD has been filled with colors corresponding to the average coordination levels in the AWM program for ACP from the Fall of 2016 to the Fall of 2020. The red polygon that encompasses parts of Los Angeles, Orange, Riverside and San Bernardino counties corresponds to the HLB quarantine zone, where HLB-positive trees have been detected and removed from residential properties. Counties colored in pink are considered to be generally infested with ACP, while counties colored in green are considered to be free of ACP (only localized detections where the population has been eradicated).

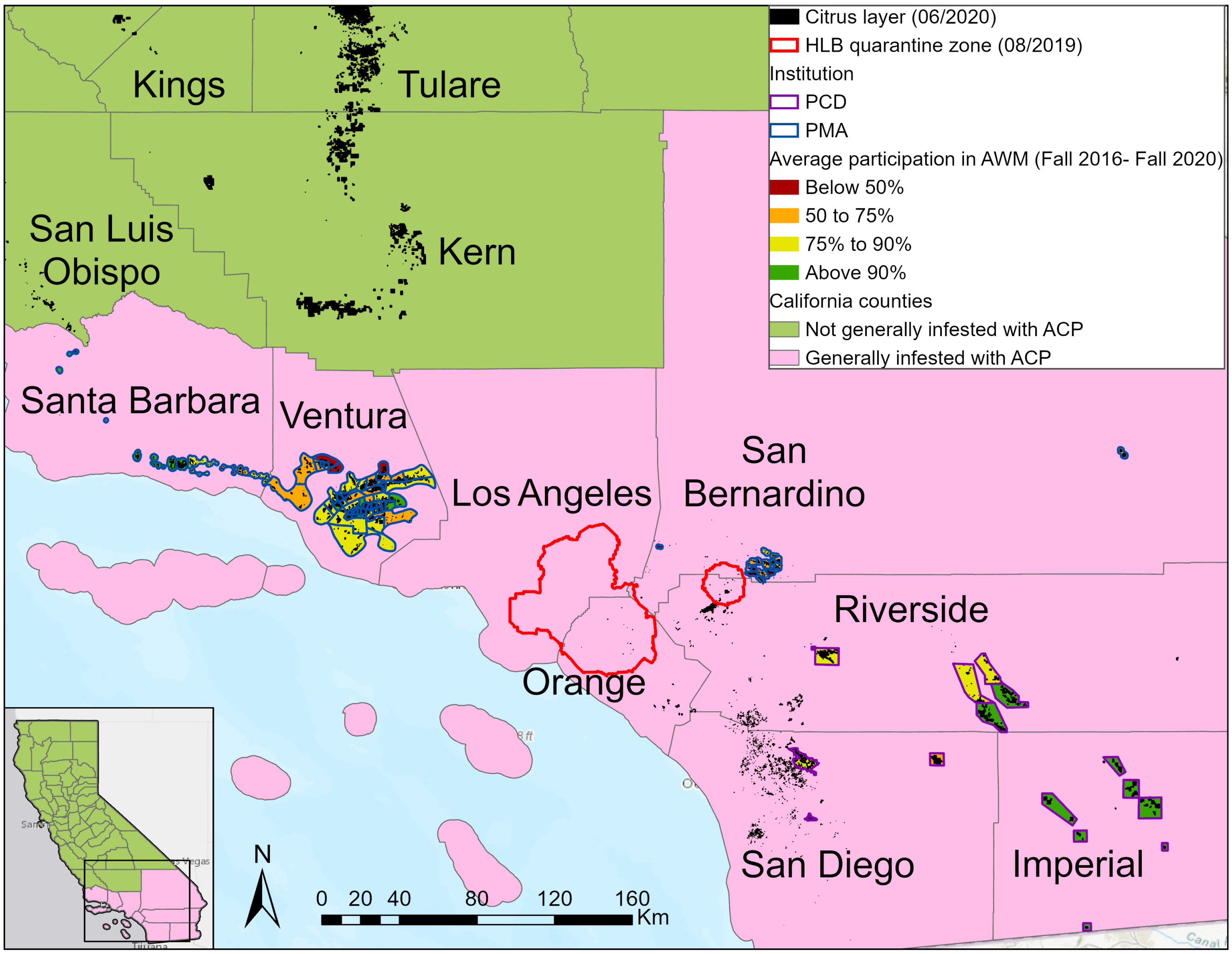


Fig. 2. Perception of area-wide management by citrus stakeholders in Southern California. The bars represent the percentage of participants who chose each response and indicated that they had citrus groves in counties that coordinate AWM treatments exclusively through PCDs (n=2), both PCDs or PMAs (n=30), or exclusively PMAs (n=66). Responses have been color-coded according to the legends on the right of each plot.

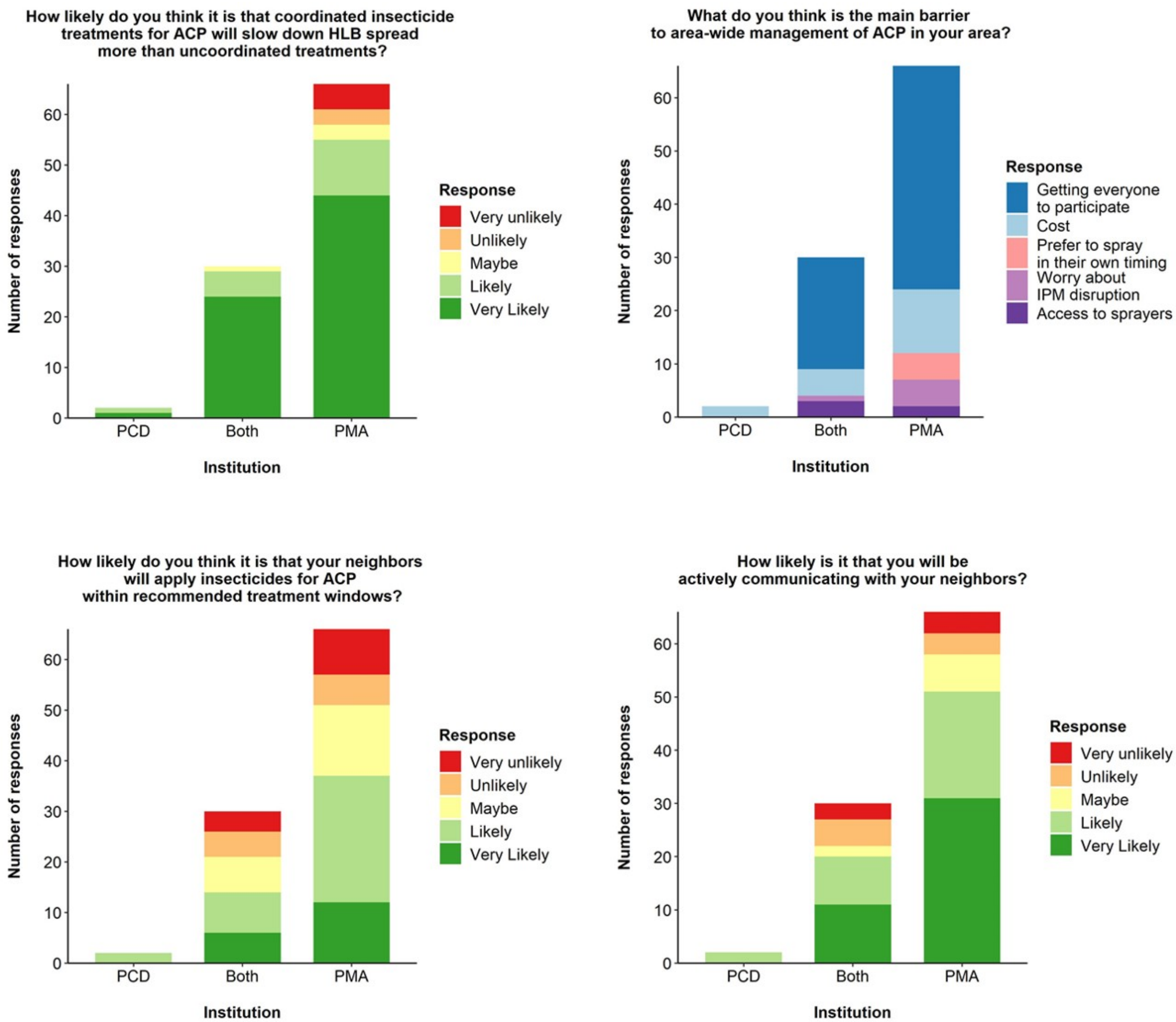


Fig. 3. Participation levels in AWM predicted by the zoib model depending on the institutional approach (PMA/PCD), the season of treatment (Fall/Winter) and the age of the program. The dots show the mean of the predicted values in blue (PMAs) or in purple (PCDs), and the shaded areas correspond to the 95% CI of the mean. Predicted values for fall treatments are linked by solid lines and predicted values for winter treatments are linked by dashed lines.

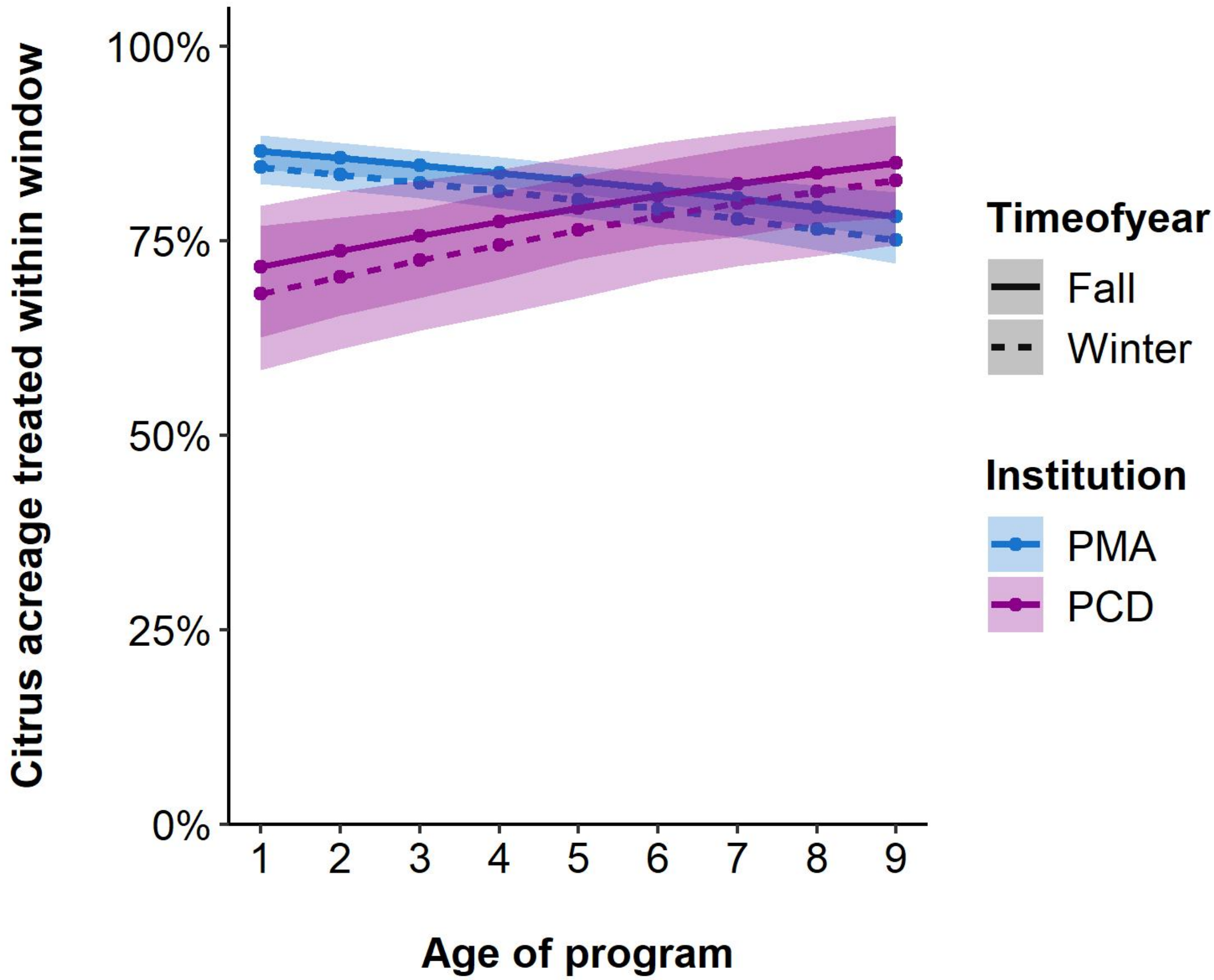


Fig. 4. Participation levels in AWM predicted by the zoib model depending on the number of pesticide use permits. The mean of the predicted values for season number 9 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines.The black dots correspond to the observed participation values and their corresponding number of permits during the last season (the Fall of 2020).

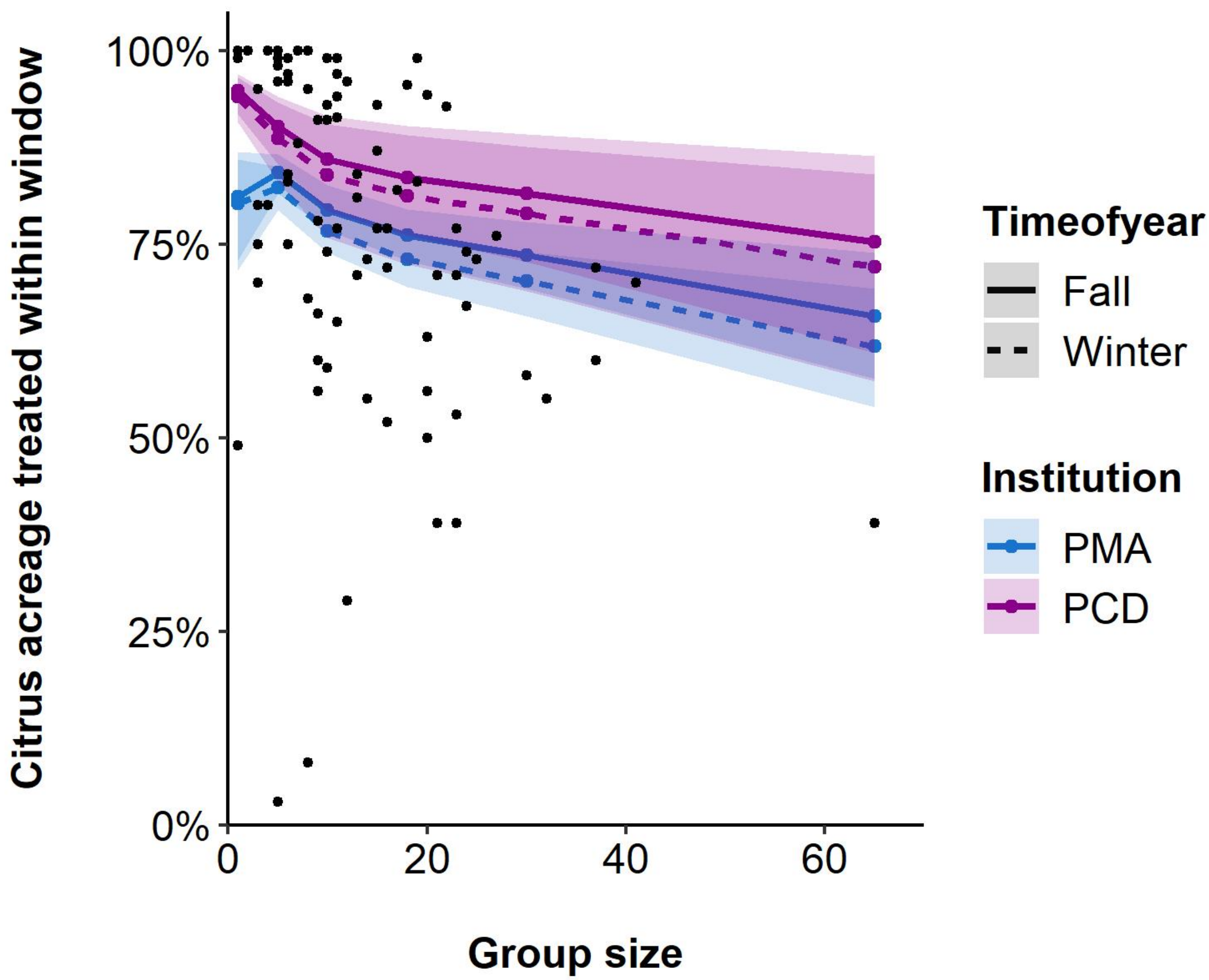
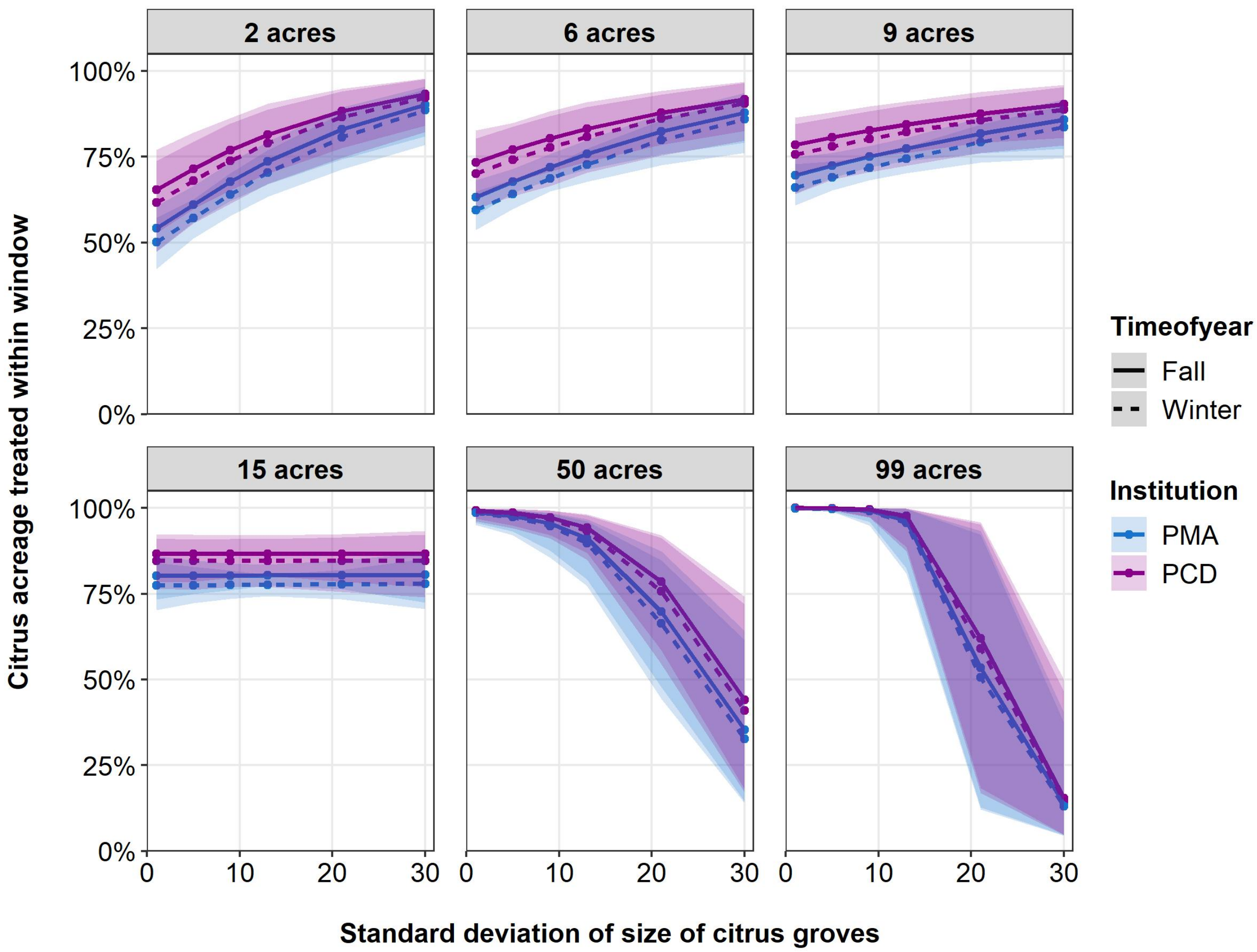


Fig. 5. Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and the heterogeneity in grove size. The mean of the predicted values for season number 9 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit. The plots corresponding to other values of the age of the program are shown in Figs. A3.4-A3.11 in Appendix 3.



Appendix 1: Survey questionnaire

1. What is your main role in citrus production?

a. Grove owner

b. Ranch manager

c. Pest Control Adviser (PCA)

d. Pest Control Operator (PCO)

e. Other

2. How many acres of citrus do you grow or manage?

a. <5 acres

b. 5-25

c. 26-100

d. 101-500

e. >500

3. What age group are you in?

a. <35 years

b. 35-50

c. 51-65

d. >65 years

4. Where are your groves located? (click all that apply)

a. Fresno

b. Imperial

c. Kern

d. Madera

e. Riverside

f. San Bernardino

g. San Diego

h. Santa Barbara

i. Tulare

j. Ventura

5. How do you grow citrus?

a. Conventionally

b. Organically

c. Both

6. What percentage of your income comes from citrus?

a. 0-25%

b. 26-50%

c. 51-75%

d. 76-100%

7. How likely do you think it is that an HLB-positive tree will be detected in your grove in the next year?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

8. How likely is it that you will stay informed about HLB and actively communicate with your grower liaison?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

f. I don’t know who my liaison is

9. How likely is it that you will be actively communicating with your neighbors (growers and homeowners)?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

11. How likely do you think it is that <u>coordinated</u> insecticide treatments for ACP will slow down HLB spread <u>more than uncoordinated</u> treatments?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

12.What do you think is <u>the main barrier</u> to area-wide management of ACP in your area? (read the whole list before you choose)

a. Preference to spray in one’s own timing

b. Access to sprayers

c. Cost

d. Getting everyone to participate

e. Disruption of IPM

13. How likely do you think it is that your neighbors will apply insecticides for ACP within recommended treatment windows?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

Text A1.2: Data analysis

All statistical analyses were done in the R programming environment version 4.0.3 (R Foundation for Statistical Computing 2020) with a Windows 10 Pro version 1909, 64-bit operating system (Microsoft, Redmond, WA, U. S. A.). Data manipulation and descriptive statistics were conducted using the R package “dplyr” (Wickham et al. 2021) and base R. Plots were generated with the R package “ggplot2” (Wickham 2016).

Analysis of survey data

Correlations between ordered categorical variables from the survey were tested using Spearman’s rank correlation test.

Analysis of participation in AWM

Four of the independent variables in the regression model (group size, size of the resource system, size of citrus groves, heterogeneity in grove size) were based on information recorded in the database of citrus operations in California maintained by the Citrus Research Board (CRB), hereafter referred to as the *citrus layer*. We obtained access to the June 2020 version of the citrus layer (Rick Dunn, personal communication) and the outlines of each AWM unit in the state of California (Rick Dunn and Robert Johnson, pers. com.). The software ArcGIS Pro (ESRI, Redlands, CA, U. S. A.) was used to overlay the citrus layer and the institutional layer in order to calculate the group size, size of the resource system, size of citrus groves and heterogeneity in grove size in each AWM unit using the “Dissolve” tool. Correlations between numeric independent variables in the regression model were tested using Pearson’s correlation test.

- Group size: It was calculated as the number of different PURs within each AWM unit on the CRB citrus layer, which was compared with the number of PURs routinely collected by the grower liaisons and found to be highly correlated (ρ=0.72, *P*=2E-15).
- Size of the resource system: It was calculated by aggregating all of the citrus properties in each PMA/PCD and calculating the sum of the grove acres. The calculated total citrus acreage under each management unit was highly correlated with data provided by the grower liaisons (ρ=0.97, *P*<2.2E-16) and with the citrus acreage recorded in the California Statewide Crop Mapping database (ρ=0.98, *P*<2.2E-16) (Department of Water Resources 2020).
- Size of citrus groves: It was calculated with the “Dissolve” tool from the software ArcGIS Pro by aggregating all of the citrus properties in each PMA/PCD and calculating the mean of the grove acres.
- Heterogeneity in grove size: It was calculated with the “Dissolve” tool from the software ArcGIS Pro by aggregating all of the citrus properties in each PMA/PCD and calculating the standard deviation of the grove acres.

Some preliminary statistical analyses were conducted to guide the hypotheses tested with the zoib regression model.

- Institutional approach (PMA/PCD): there was significantly higher participation in AWM in PCDs than PMAs in every season ($P \leq 0.043$ on t-tests), except the Fall of 2016 ($P=0.99$).
- Group size: there was a significant negative correlation between the number of pesticide use permits and participation in AWM ($\rho=-0.28$, $P<2.2E-16$).
- Size of citrus groves: there was a significant positive correlation between the average size of citrus groves and participation in AWM ($\rho=0.27$, $P \leq 2.2E-16$).

Zero-and-one-inflated beta regression models were constructed using the R package "zoib" (Liu and Kong 2015). A zoib model assumes that the dependent variable *y* (the percentage of citrus acreage in each PMA/PCD treated within the recommended window) follows a piecewise distribution such that

$$f(y_i) = \begin{cases} p_i & \text{if } y_i = 0 \\ (1-p_i)q_i & \text{if } y_i = 1 \\ (1-p_i)(1-q_i)\mathrm{Beta}(\alpha_{i1}, \alpha_{i2}) & \text{if } y_i \in (0,1) \end{cases}$$

where p_i represents the probability $\Pr(y_i=0)$, q_i represents the conditional probability $\Pr(y_i=1|y_i \neq 0)$, and α_{1i} and α_{2i} represent the shape parameters of the beta distribution for $y_i \in (0,1)$. These distributions are combined to derive the unconditional estimate of the response $E(y_i)$:

$$E(y_i) = (1-p_i)(\, q_i + (1-q_i)\mu_i^{(0,1)}$$

The zoib regression model estimates the logit [*i.e.*, the log(odds)] of the expected value of the beta distribution, the logit of $P(0)$ and $P(1)$ and the log of the dispersion of the beta distribution as linear functions of fixed and/or random effects. The coefficients of the effects on the mean of the beta regression can be interpreted as the expected change in the logit of participation with a one unit change in the corresponding variable. The coefficients of the effects on P(0) and P(1) are interpreted as the change in the logit of either having Participation=0 or Participation=1 with a one unit change in the corresponding variable. The coefficients of the effects on the dispersion of the beta distribution indicate the change in the log of the dispersion with a one-unit change in the corresponding variable (van Woerden et al. 2019). Based on a Bayesian framework, the coefficients are estimated through a Markov Chain Monte Carlo (MCMC) approach (Liu and Kong 2015). Two independent MCMC chains were run per model, each with 5000 iterations, including 200 iterations for burn-in, and thinned by a factor of 2. We assumed a Normal prior distribution N(0, 0.001) for each regression coefficient.

MCMC convergence was visually checked with trace plots and autocorrelation plots. The potential scale reduction factor (psrf) was calculated for each model parameter and the threshold psrf≤1.1 was used to determine that convergence had been reached (Gelman et al. 2021). In cases where psrf>1.1, we repeated the MCMC process with three chains, 10000 iterations per chain, 1000 for burn-in and thinned by a factor of 50. Posterior inferences for each parameter are reported as the mean and 95% credible interval (CI). Model selection was based on the deviance information criterion (DIC) (Liu and Kong 2015). Starting with the most complex model including the seven independent variables mentioned in the previous section, we examined the results and iteratively removed variables for which the CI of the posterior estimates was bounded by a negative and a positive value, and therefore comprised zero. Among competing models that fulfilled the previous condition, we chose the one with the lowest DIC (Table A4.1, Table A4.2).

Finally, the participation levels predicted by the zoib regression model were calculated using the pred.zoib function in the R package "zoib" (Liu and Kong 2015). Predictions were based on a new dataset where the independent variable under evaluation was allowed to vary within the range observed in the original dataset and the rest of the independent variables were fixed at their mean value, except in the case of interaction terms, where both variables were allowed to vary within the observed range.

All the R code used in this study will be posted in a repository at the following URL after publication: https://github.com/nmcr01?tab=repositories.

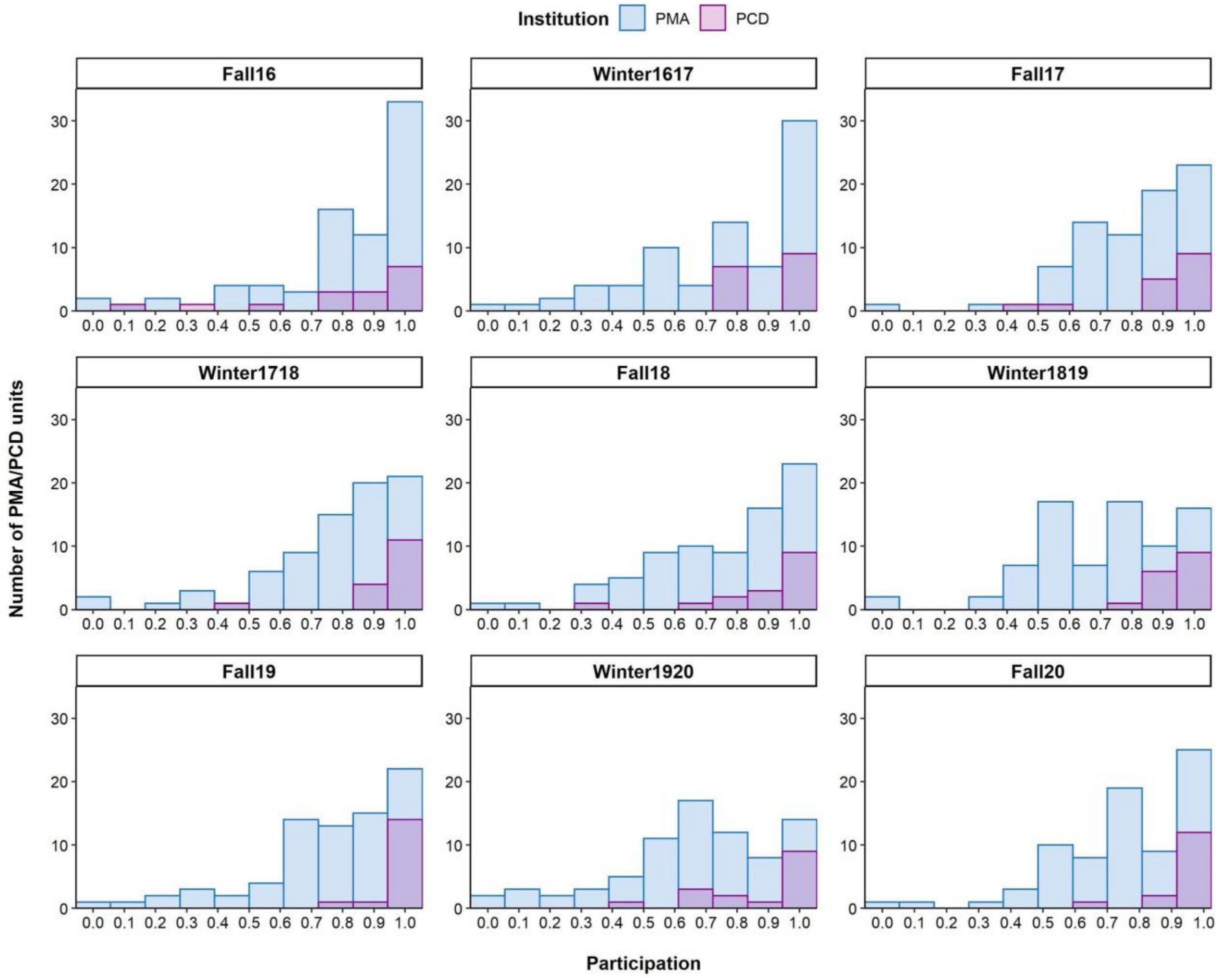


Fig. S1: Histogram of participation levels in area-wide management in Psyllid Management Areas (blue) and Pest Control Districts (purple) over nine seasons.

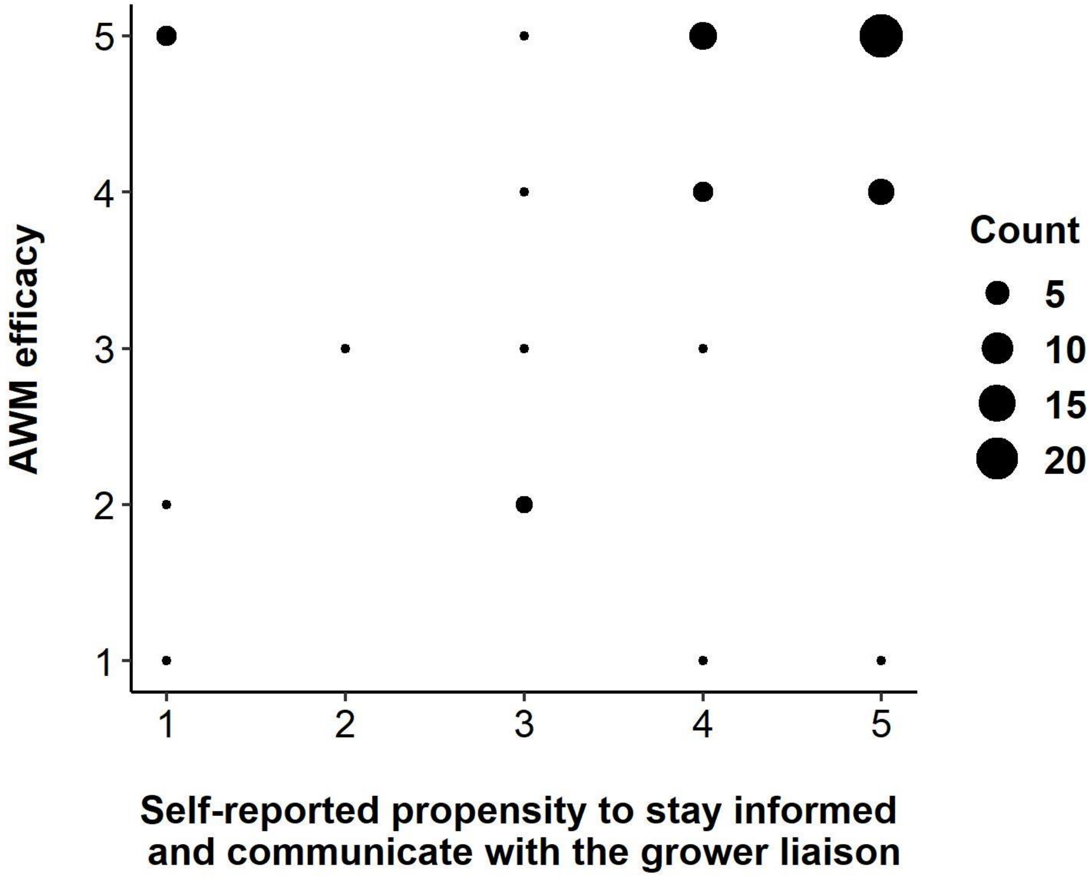


Fig. S2: Relationship between the self-reported propensity to stay informed and communicate with the grower liaison and the belief that coordinated insecticide treatments for ACP will slow down HLB spread more than uncoordinated treatments (AWM efficacy). Responses to the survey questions were transformed to numeric so that *very unlikely* = 1, *unlikely* = 2, *maybe* = 3, *likely* = 4, *very likely* = 5. The size of the points represents the number of participants who chose that combination of responses.

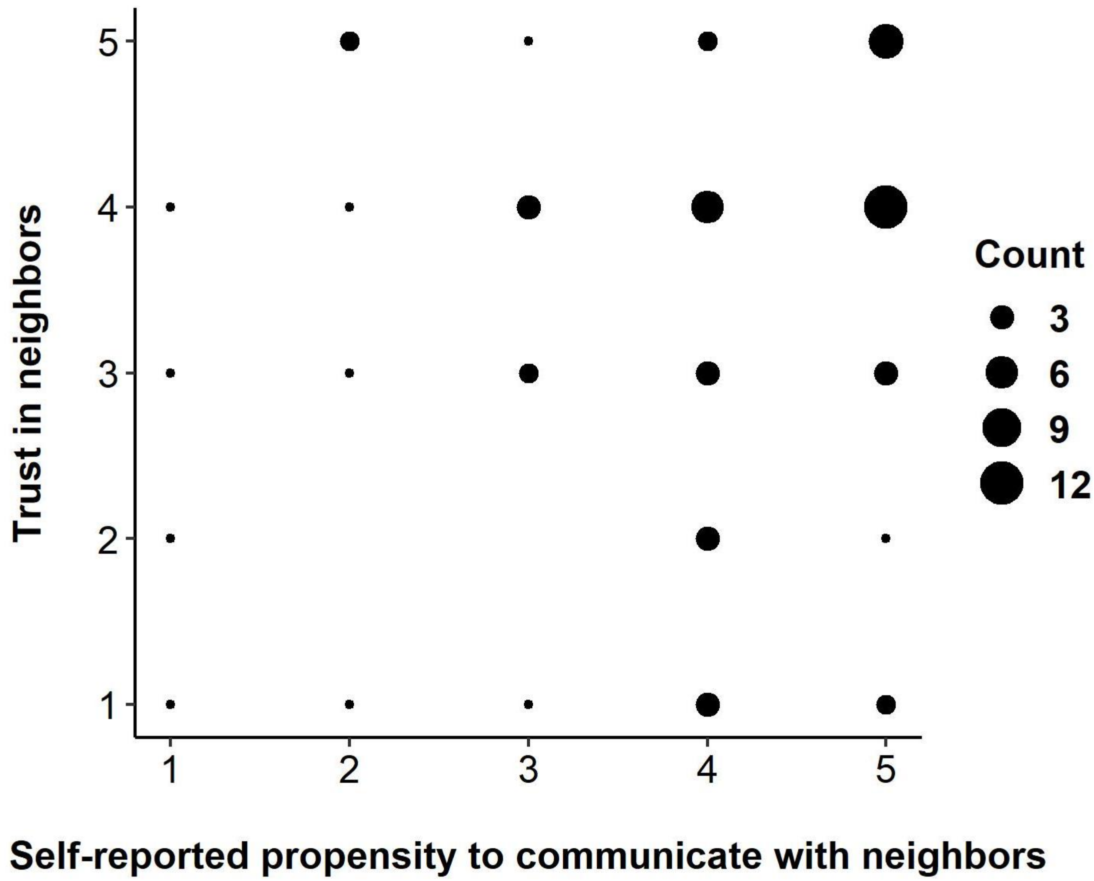


Fig. S3: Relationship between the self-reported propensity to communicate with neighbors and the belief that neighbors will apply insecticides for ACP within the recommended treatment window (trust in neighbors). Responses to the survey questions were transformed to numeric so that *very unlikely* = 1, *unlikely* = 2, *maybe* = 3, *likely* = 4, *very likely* = 5. The size of the points represents the number of participants who chose that combination of responses.

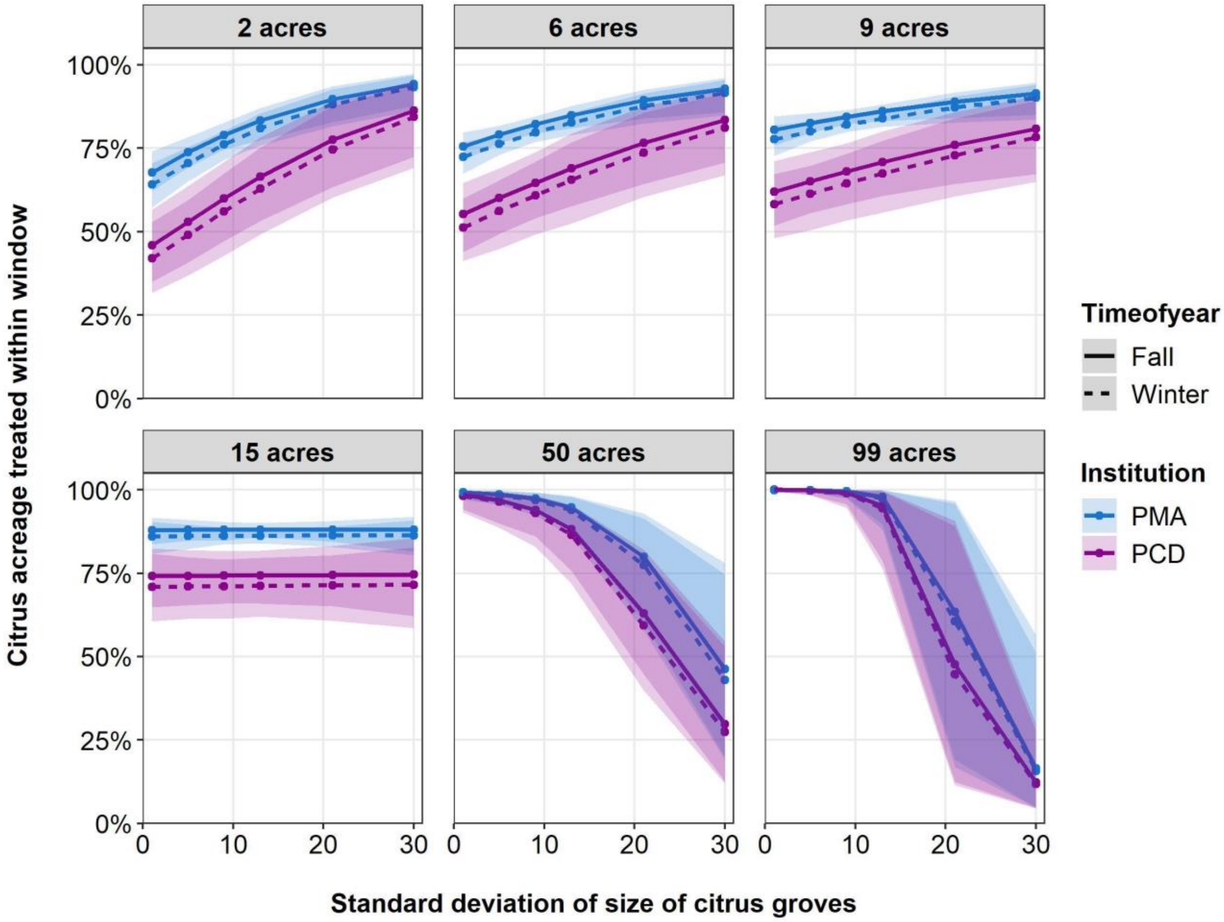


Fig. S4: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 1 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

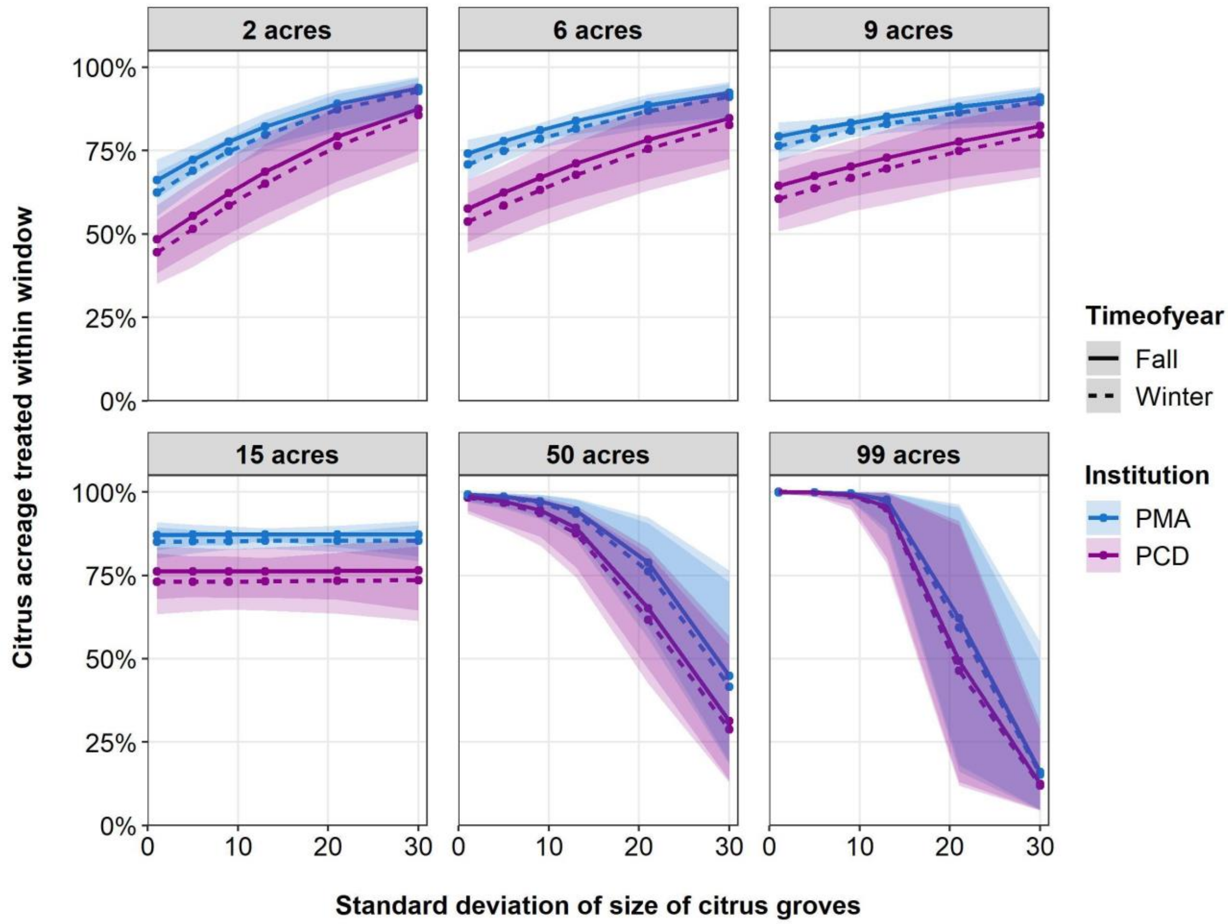


Fig. S5: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 2 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

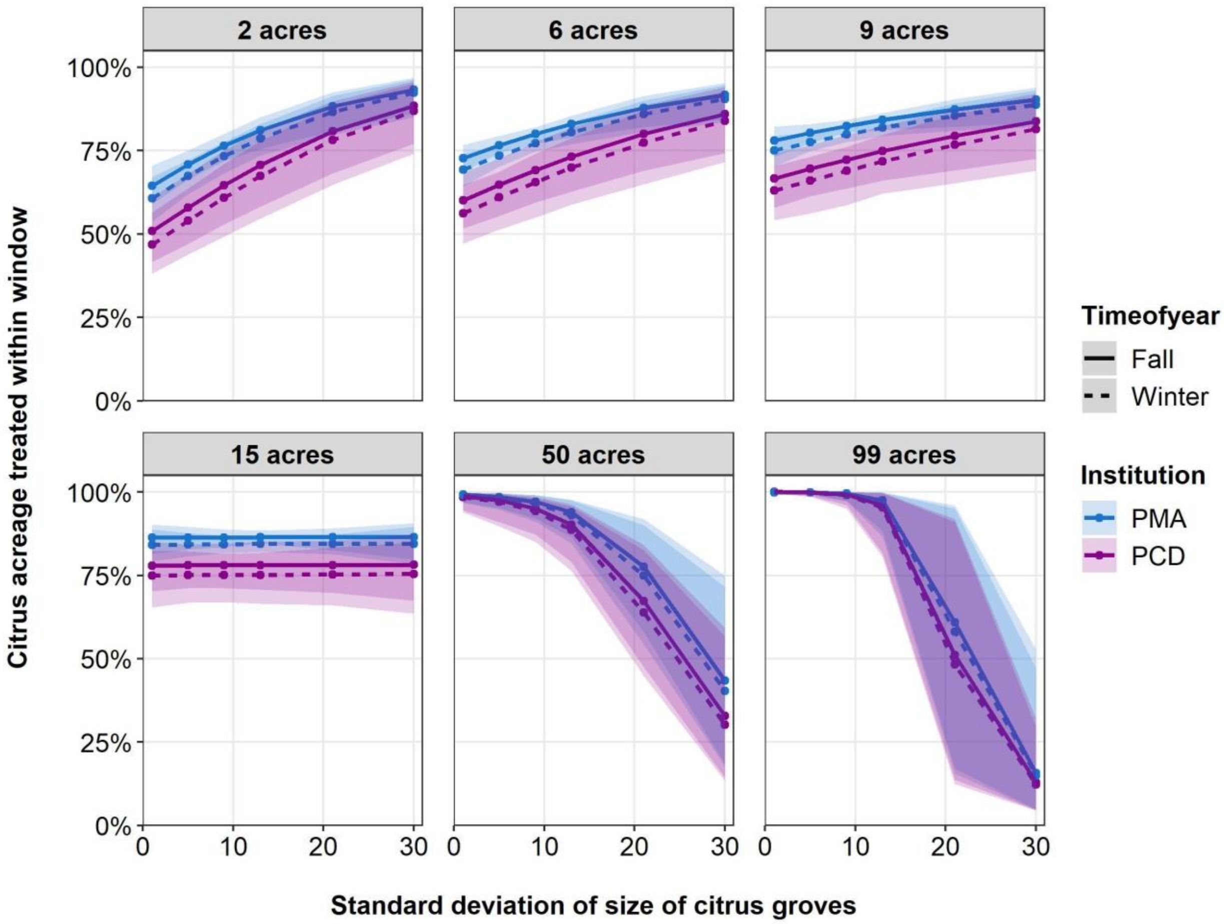


Fig. S6: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 3 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

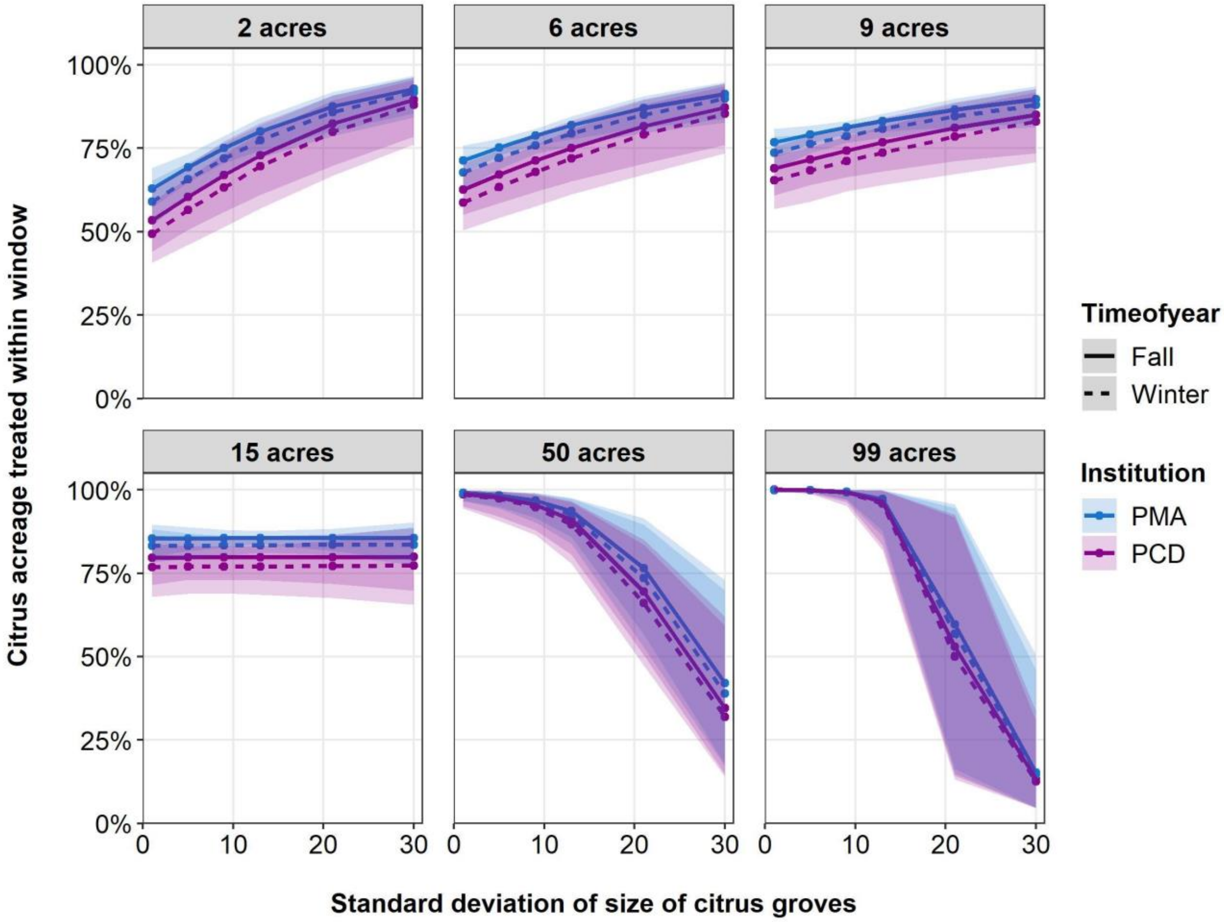


Fig. S7: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 4 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

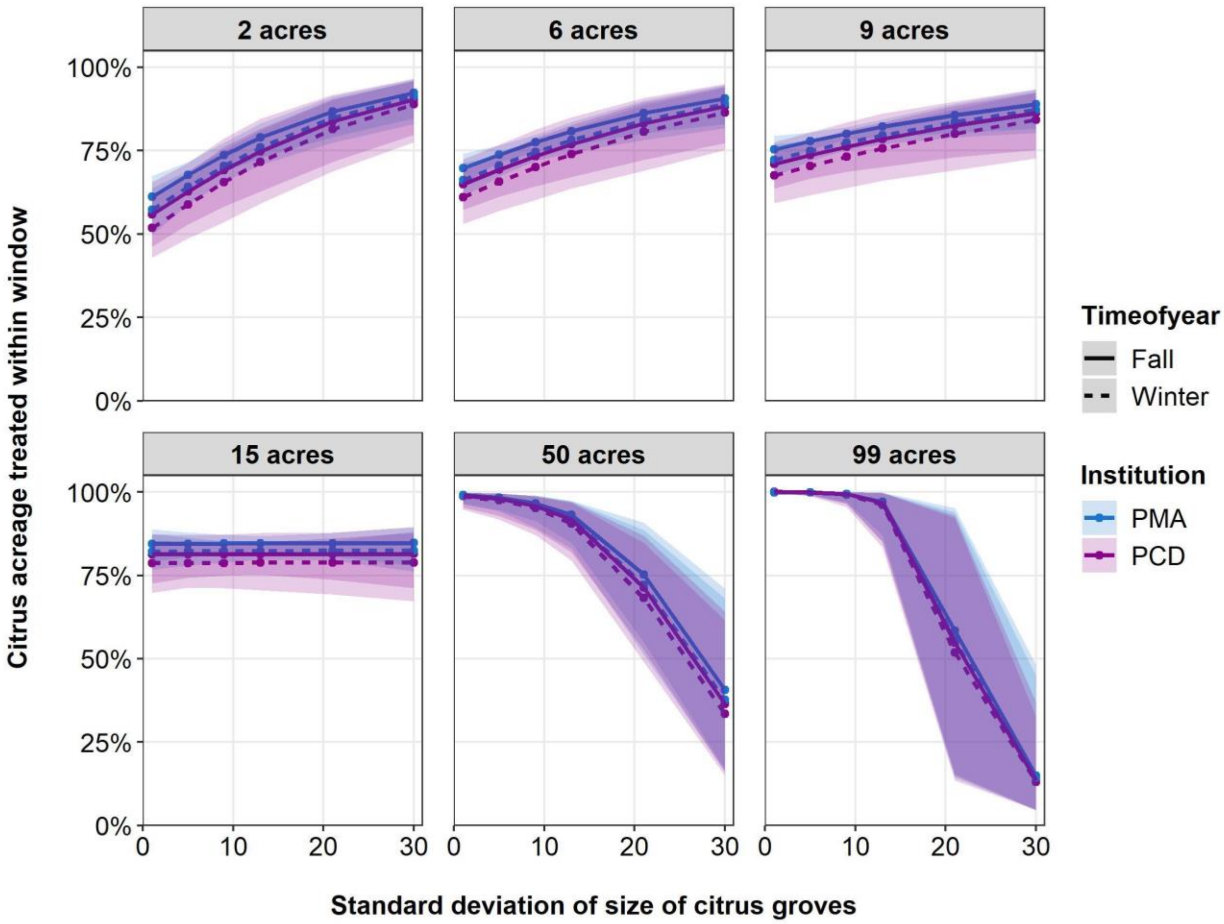


Fig. S8: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 5 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

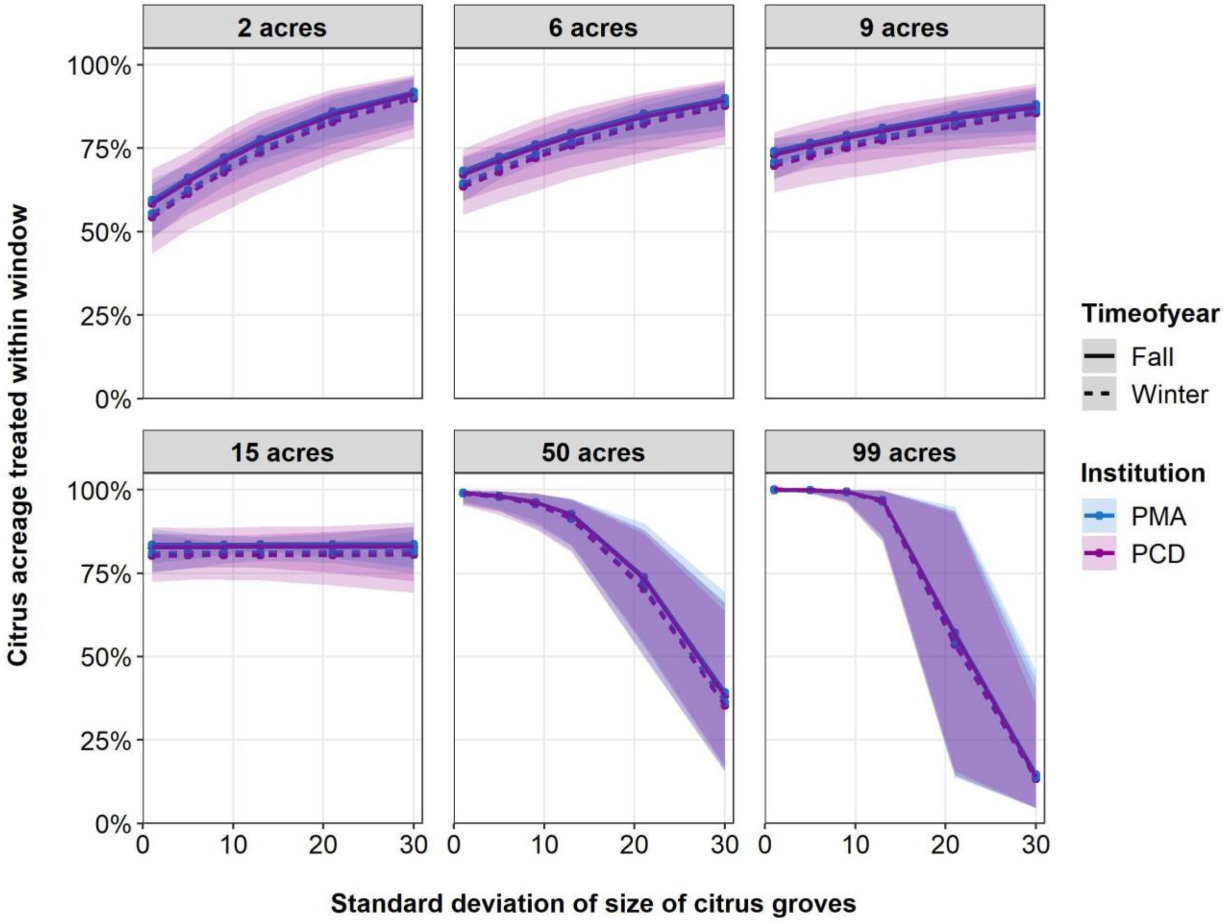


Fig. S9: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 6 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

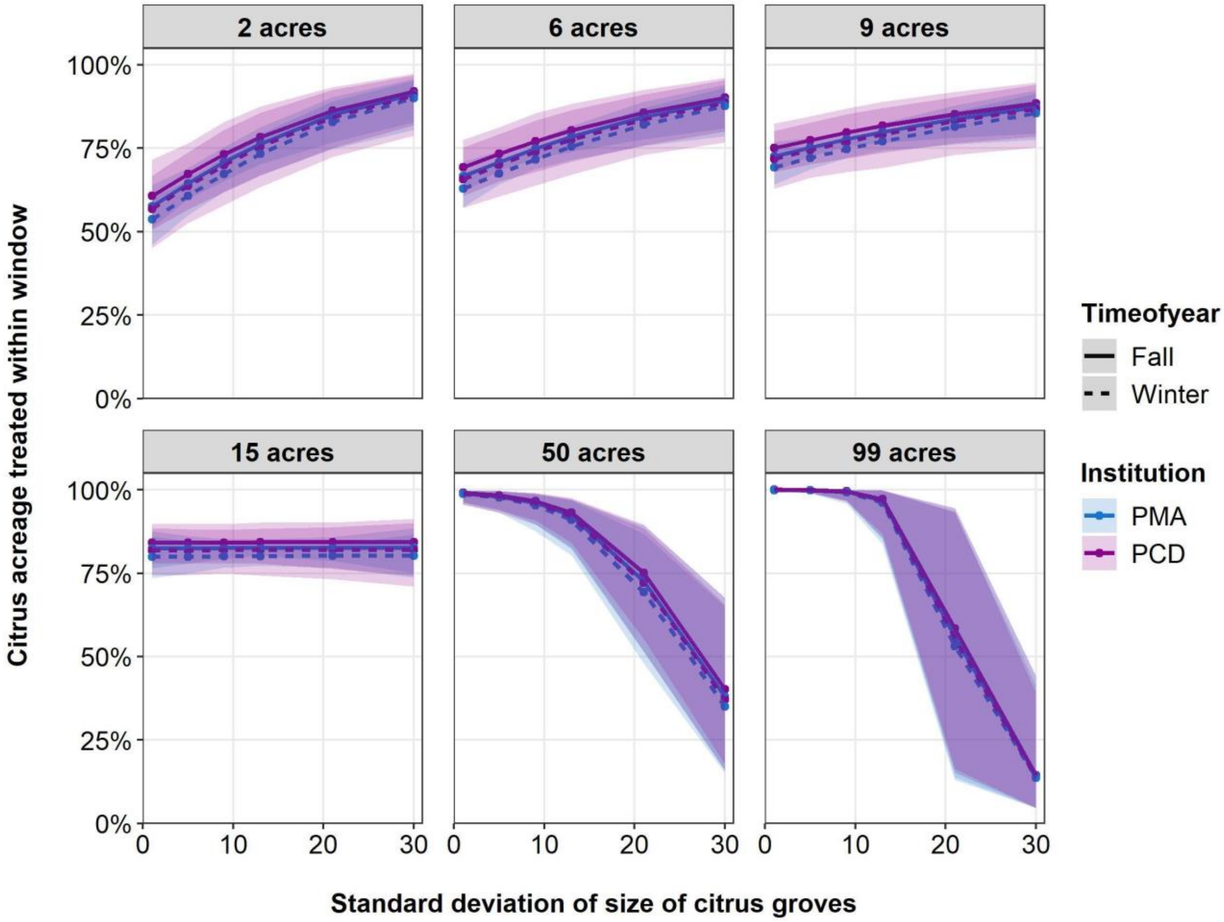


Fig. S10: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 7 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

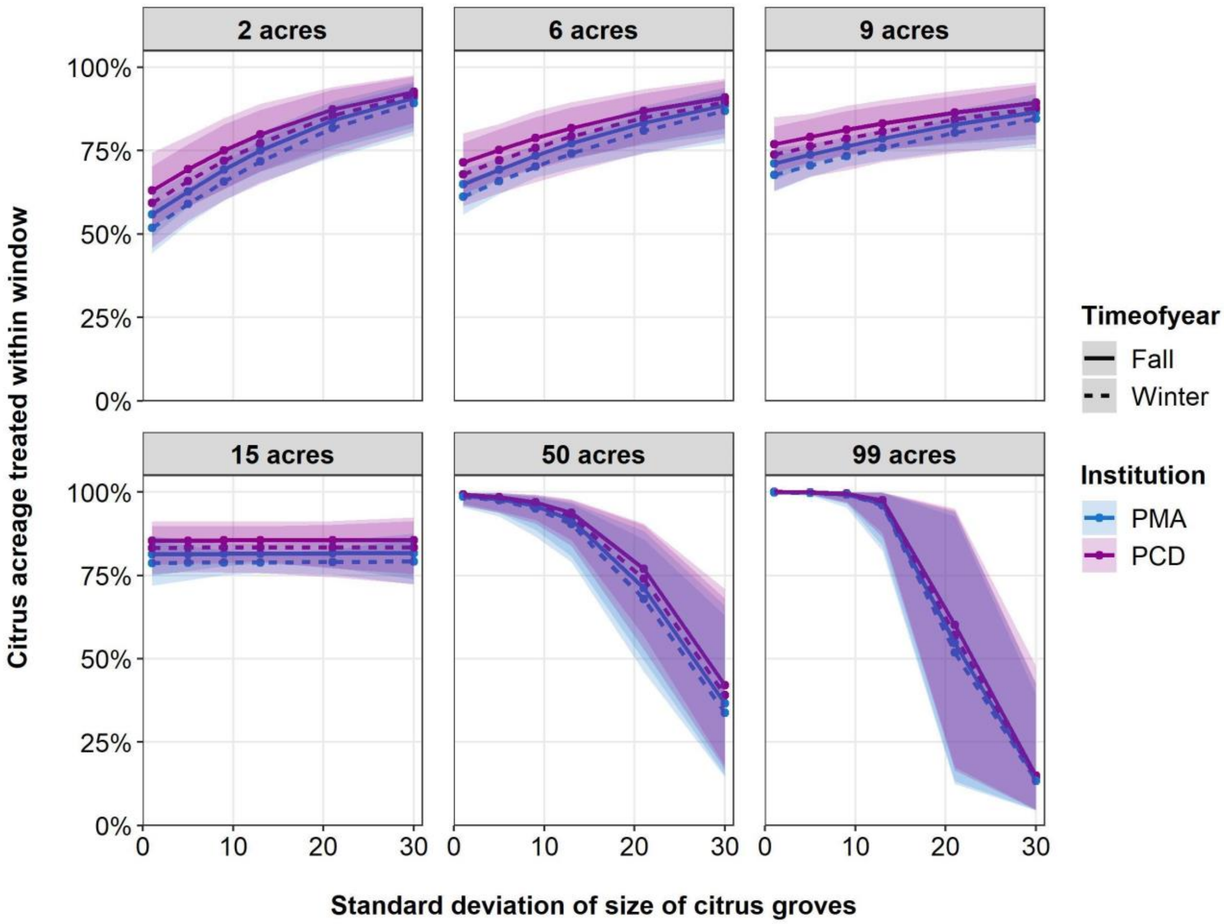


Fig. S11: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 8 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

Table S1: Institutions coordinating area-wide management of ACP in Southern California.

County	Institution	History	Citrus acreage	Assessment rate (2018)	Coordinated treatments	Number of management units	Using PMAs?	Participation in AWM	Challenges	Other activities
Imperial	Imperial County Citrus Pest Control District	Formed in 1972 for California red scale (*Aonidiella aurantii*) control[1]. Expanded in 2013 to the whole county for ACP and HLB control[2]	7,200	$15 / acre	Fall (Aug-Oct, Winter (Dec-Jan), Spring (Feb-Apr)	7 (6 after 2020)	No, PCD growing zones	High	ACP from across the Mexican border	Outreach, trap monitoring, coordination with Mexican authorities
Riverside	Citrus Pest Control District No. 2 (Coachella	Formed in 1946 for California red scale	8,000	$150 / acre	Fall (Sep-Oct), Winter (Dec-Jan)	4	No, four zones	High, reimbursing for treatments	Reinfestation from residential areas	Tree removal, biocontrol

	Valley)	control[3]								
	Citrus Pest Control District No. 3 (Hemet)	Formed in 2017 for ACP and HLB control	2,134	$100/ acre	Fall (Sep), Winter (Dec-Jan)	2	No, two zones	Very high, three growers. Reimbursing for treatments	Reinfestation from residential areas	Funding some activities in residential areas
	Rest of the county	No entity directing the sprays	1,500	None	Fall, Winter			Low, not tracked	Absentee owners, small growers	UC Riverside promoting participation
San Bernardino	San Bernardino ACP/ HLB Task Force	Formed in 2014[4]	3,000	None	Fall (Oct-Nov), Winter (Nov-Dec), Spring (May-Jul)	19	Yes	Variable	Small growers, scarcity of PCOs, urban interface, water supply, bad actors	Grower liaison in contact with homeowners, reporting abandoned trees
San Diego	San Diego County Citrus Pest Control District	Formed in 2017 for ACP and HLB control[5]	4,500	$180 / acre	Fall (Aug-Sep), Winter (Jan), Spring (May-Jun)	3	No, three areas (Borrego Springs, San Pasqual, Pauma/Pala	Variable when it was voluntary. Now higher because of assessment reimbursements	Problems with organic treatments, small growers	County authorities monitor abandoned trees and try to remove them

							Valley)			
Santa Barbara	Advisory committee	Formed in 2015 for ACP and HLB control[6]	4,425	None	Fall (Sep), Winter (Jan)	12 (11 after 2019)	No, treating by cities	High	Weather, small properties	
Ventura	Ventura ACP/HLB Task Force	Formed in 2010 for ACP and HLB control[7]	25,000	None	Fall (Jul-Sep + Sep-Nov), Winter (Jan-Mar), Spring (Apr-Jun)	50	Yes	High	Spraying equipment shortage, continuous harvest, weather, movement of fruit	Outreach campaign in residential areas, reporting system for abandoned trees

[1] (Margo Sanchez, pers. comm.), [2] (Mark McBroom, pers. comm.), [3](Baker 1988), [4](Bob Atkins, pers. comm.), [5](Cressida Silvers, pers. comm.),[6](SDCCPCD 2021), [7](John Krist, pers. comm.)

Table S2: Socio-economic characteristics of the survey respondents who indicated that they had citrus groves in Southern California (n =98).

Survey item	Responses
Role in citrus production	
Grove Owner	38
Ranch Manager	17
PCA	18
PCO	2
Other	18
NA	5
Farm size	
< 5 acres	23
5 – 25 acres	18
26 – 100 acres	11
101 – 500 acres	13
> 500 acres	28
NA	5
Age	
<35 years	12
35 - 50 years	14
51 – 65 years	37
> 65 years	35
Management system	
Conventional	59
Organic	13
Both	23
NA	3

Income from citrus	
< 25%	40
26 - 50%	13
51 - 75%	16
76 - 100%	23
NA	6

Note: Pest Control Adviser (PCA), Pest Control Operator (PCO), no answer (NA)

Table S3: Posterior mean and 95% credible interval for the parameters in the zoib regression models evaluated that were more complex than the selected model (SD28).

		SD22 mean	SD22 2.5%	SD22 97.5%	SD23 mean	SD23 2.5%	SD23 97.5%	SD24 mean	SD24 2.5%	SD24 97.5%	SD19 mean	SD19 2.5%	SD19 97.5%	SD28 mean	SD28 2.5%	SD28 97.5%
logit (mean)	Institutional approach[†]	-1.08	-1.67	-0.52	-1.08	-1.61	-0.53	-1.06	-1.63	-0.50	-0.68	-1.21	-0.13	-1.09	-1.65	-0.57
	Group size	-0.01	-0.02	0.00	-0.01	-0.02	0.00	-0.01	-0.02	0.00	-0.01	-0.02	-0.01	-0.01	-0.02	0.00
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Grove size	0.10	0.06	0.14	0.10	0.07	0.14	0.10	0.06	0.15	0.08	0.04	0.12	0.10	0.06	0.14
	Heterogeneity	0.08	0.05	0.12	0.09	0.05	0.12	0.09	0.05	0.12	0.12	0.08	0.15	0.08	0.05	0.12
	Season[‡]	-0.18	-0.32	-0.04	-0.17	-0.30	-0.04	-0.17	-0.29	-0.03	-0.16	-0.29	-0.03	-0.17	-0.30	-0.05
	Age	-0.07	-0.10	-0.04	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05

	Institution† x Age	0.17	0.10	0.25	0.17	0.09	0.25	0.17	0.09	0.25	0.18	0.09	0.26	0.17	0.10	0.25
	Grove size x Heterogeneity	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00
	Intercept	0.43	0.06	0.78	0.40	0.07	0.73	0.42	0.07	0.77	0.46	0.12	0.81	0.43	0.11	0.79
log(dispersion)	Institutional approach†	-0.81	-1.32	-0.30	-0.81	-1.32	-0.33	-0.80	-1.30	-0.31				-0.81	-1.30	-0.38
	Group size	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.03	0.04	0.03	0.02	0.04
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00
	Grove size	0.06	0.02	0.11	0.06	0.02	0.11	0.06	0.01	0.10				0.06	0.02	0.10
	Heterogeneity	-0.05	-0.09	-0.01	-0.05	-0.09	-0.02	-0.05	-0.09	-0.01				-0.05	-0.08	-0.02
	Season‡	-0.07	-0.27	0.13												
	Age	0.00	-0.03	0.04												
	Intercept	0.90	0.56	1.27	0.88	0.60	1.15	0.89	0.60	1.17	1.07	0.91	1.23	0.88	0.62	1.13

logit(P(1))	Institutional approach†	-92.64	-221.71	-6.68	-34.93	-85.72	-3.62	-46.39	-119.37	-3.70				-67.45	-188.90	-4.66
	Group size	-0.69	-1.21	-0.29	-0.61	-1.01	-0.31	-0.59	-1.07	-0.28	-0.49	-0.87	-0.22	-0.58	-0.93	-0.30
	Size of resource system	0.00	0.00	0.00												
	Grove size	-0.02	-0.15	0.10												
	Heterogeneity	0.04	-0.12	0.19							-0.01	-0.13	0.10			
	Season‡	0.51	-0.86	1.85												
	Age	-0.13	-0.40	0.13												
	Intercept	-1.06	-3.25	0.93	-1.37	-2.35	-0.43	-1.41	-2.45	-0.37	-2.13	-3.42	-0.96	-1.43	-2.38	-0.51
logit(P(0))	Institutional approach†	-0.22	-0.91	0.49												
	Group size	-0.31	-0.39	-0.24	-0.30	-0.37	-0.24	-0.32	-0.39	-0.26	-0.28	-0.34	-0.23	-0.32	-0.38	-0.27

Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Grove size	0.08	0.04	0.13	0.08	0.04	0.13	0.05	0.02	0.08	0.07	0.05	0.10			
Heterogeneity	-0.05	-0.11	0.00	-0.05	-0.10	0.00							0.03	0.00	0.06
Season‡	-0.36	-0.82	0.08												
Age	-0.08	-0.17	0.00												
Intercept	0.50	-0.27	1.30	-0.13	-0.74	0.46	-0.20	-0.77	0.36	-0.34	-0.91	0.22	0.54	0.10	1.04
DIC	1679813			1679811			1679814			1679852			1679849		
Multivariate psrf	1.39			1.05			1.20			1.01			1.10		

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

Table S4: Posterior mean and 95% credible interval for the parameters in the zoib regression models evaluated that were less complex than the selected model (SD28).

		SD27 mean	SD27 2.5%	SD27 97.5%	SD29 mean	SD29 2.5%	SD29 97.5%	SD30 mean	SD30 2.5%	SD30 97.5%	SD31 mean	SD31 2.5%	SD31 97.5%	SD13 mean	SD13 2.5%	SD13 97.5%	SD21 mean	SD21 2.5%	SD21 97.5%	SD0 mean	SD0 2.5%	SD0 97.5%
logit (mean)	Institutional approach†	-1.08	-1.64	-0.51	-1.34	-1.89	-0.83	-0.24	-0.68	0.20	-0.54	-0.97	-0.13	-0.67	-1.17	-0.13	-0.58	-1.13	-0.03			
	Group size	-0.01	-0.02	0.00	-0.02	-0.02	-0.01	-0.01	-0.02	0.00	-0.02	-0.02	-0.01	-0.01	-0.02	-0.01	-0.02	-0.03	-0.01			
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Grove size	0.10	0.07	0.14	0.03	0.00	0.06	0.10	0.06	0.14	0.03	0.00	0.05	0.08	0.04	0.12	0.09	0.05	0.12			
	Heterogeneity	0.08	0.04	0.12	0.02	-0.01	0.05	0.08	0.05	0.12	0.02	-0.01	0.05	0.12	0.08	0.15	0.13	0.09	0.16			
	Season‡	-0.17	-0.29	-0.04	-0.15	-0.28	-0.02	-0.17	-0.30	-0.04	-0.15	-0.28	-0.03	-0.16	-0.29	-0.03	-0.16	-0.30	-0.02			

	Age	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.06	-0.08	-0.03	-0.06	-0.08	-0.03	-0.07	-0.10	-0.05	-0.07	-0.10	-0.04			
	Institution† x Age	0.17	0.09	0.25	0.16	0.08	0.24							0.18	0.09	0.26	0.17	0.08	0.26			
	Grove size x Heterogeneity	-0.01	-0.01	0.00				-0.01	-0.01	0.00				-0.01	-0.01	0.00	-0.01	-0.01	0.00			
	Intercept	0.41	0.07	0.76	1.05	0.79	1.30	0.34	-0.01	0.69	0.96	0.71	1.23	0.47	0.12	0.81	0.51	0.17	0.86	1.06	0.98	1.15
log (dispersion)	Institutional approach†	-0.82	-1.32	-0.33	-0.88	-1.38	-0.40	-0.89	-1.38	-0.41	-0.95	-1.44	-0.44									
	Group size	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.03	0.04						
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00									
	Grove size	0.06	0.02	0.11	0.06	0.02	0.10	0.07	0.03	0.11	0.07	0.03	0.11									

	Heterogeneity	-0.05	-0.09	-0.02	-0.06	-0.10	-0.02	-0.06	-0.09	-0.02	-0.06	-0.10	-0.03									
	Season‡																					
	Age																					
	Intercept	0.88	0.60	1.16	0.87	0.60	1.16	0.87	0.59	1.14	0.87	0.59	1.14	1.07	0.91	1.23	1.53	1.42	1.63	1.24	1.14	1.34
logit (P(1))	Institutional approach†																					
	Group size	-0.47	-0.83	-0.23	-0.48	-0.89	-0.23	-0.47	-0.84	-0.22	-0.51	-0.91	-0.24	-0.49	-0.85	-0.22						
	Size of resource system																					
	Grove size																					
	Heterogeneity																					
	Season‡																					
	Age																					

	Intercept	-2.22	-3.12	-1.36	-2.17	-3.10	-1.31	-2.21	-3.12	-1.35	-2.14	-3.06	-1.27	-2.17	-3.10	-1.30	-4.37	-5.00	-3.79	-4.37	-5.03	-3.79
logit (P(0))	Institutional approach†																					
	Group size	-0.32	-0.38	-0.27	-0.32	-0.38	-0.26	-0.32	-0.38	-0.26	-0.32	-0.38	-0.26	-0.31	-0.37	-0.26						
	Size of resource system																					
	Grove size																					
	Heterogeneity	0.03	0.00	0.07	0.03	0.00	0.07	0.03	0.00	0.07	0.03	0.00	0.07									
	Season‡																					
	Age																					
	Intercept	0.53	0.06	1.01	0.53	0.05	1.00	0.53	0.05	1.02	0.53	0.05	1.03	0.89	0.55	1.25	-1.43	-1.61	-1.25	-1.43	-1.60	-1.26
	DIC	1679860			1679885			1679877			1679900			1679883			1680225			1680402		

Multivariate psrf	1.04	1.02	1.05	1.05	1.02	1.05	1

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

Table S5: Posterior mean and 95% credible interval for the parameters in the selected zoib regression model (SD28) with the size of the resource system, and the model without this independent variable (SD32).

		SD28 mean	SD28 2.5%	SD28 97.5%	SD32 mean	SD32 2.5%	SD32 97.5%
logit(mean)	Institutional approach†	-1.09	-1.65	-0.57	-0.65	-1.17	-0.13
	Group size	-0.01	-0.02	0.00	-0.01	-0.01	0.00
	Size of resource system	0.00	0.00	0.00			
	Grove size	0.10	0.06	0.14	0.13	0.09	0.16
	Heterogeneity	0.08	0.05	0.12	0.10	0.07	0.13
	Season‡	-0.17	-0.30	-0.05	-0.17	-0.31	-0.04
	Age	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05
	Institution† x Age	0.17	0.10	0.25	0.17	0.09	0.26
	Grove size x Heterogeneity	-0.01	-0.01	0.00	-0.01	-0.01	-0.01
	Intercept	0.43	0.11	0.79	0.26	-0.06	0.58
log(dispersion)	Institutional approach†	-0.81	-1.30	-0.38	-0.42	-0.82	0.01
	Group size	0.03	0.02	0.04	0.04	0.03	0.05
	Size of resource system	0.00	0.00	0.00			
	Grove size	0.06	0.02	0.10	0.07	0.03	0.11
	Heterogeneity	-0.05	-0.08	-0.02	-0.05	-0.08	-0.02
	Season‡						

	Age						
	Intercept	0.88	0.62	1.13	0.88	0.62	1.15
logit(P(1))	Institutional approach†	-67.45	-188.90	-4.66	-53.65	-126.63	-3.99
	Group size	-0.58	-0.93	-0.30	-0.58	-0.94	-0.30
	Size of resource system						
	Grove size						
	Heterogeneity						
	Season‡						
	Age						
	Intercept	-1.43	-2.38	-0.51	-1.42	-2.39	-0.47
logit(P(0))	Institutional approach†						
	Group size	-0.32	-0.38	-0.27	-0.32	-0.37	-0.27
	Size of resource system						
	Grove size						
	Heterogeneity	0.03	0.00	0.06	0.03	0.00	0.07
	Season‡						
	Age						
	Intercept	0.54	0.10	1.04	0.54	0.06	1.04
	DIC	1679849			1679861		
	Multivariate psrf	1.10			1.33		

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

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Appendix 2: Data analysis

All statistical analyses were done in the R programming environment version 4.0.3 (R Foundation for Statistical Computing 2020) with a Windows 10 Pro version 1909, 64-bit operating system (Microsoft, Redmond, WA, U. S. A.). Data manipulation and descriptive statistics were conducted using the R package "dplyr" (Wickham et al. 2021) and base R. Plots were generated with the R package "ggplot2" (Wickham 2016).

Analysis of survey data

Correlations between ordered categorical variables from the survey were tested using Spearman's rank correlation test.

Analysis of participation in AWM

Four of the independent variables in the regression model (group size, size of the resource system, size of citrus groves, heterogeneity in grove size) were based on information recorded in the database of citrus operations in California maintained by the Citrus Research Board (CRB), hereafter referred to as the *citrus layer*. We obtained access to the June 2020 version of the citrus layer (Rick Dunn, personal communication) and the outlines of each AWM unit in the state of California (Rick Dunn and Robert Johnson, pers. com.). The software ArcGIS Pro (ESRI, Redlands, CA, U. S. A.) was used to overlay the citrus layer and the institutional layer in order to calculate the group size, size of the resource system, size of citrus groves and heterogeneity in grove size in each AWM unit using the "Dissolve" tool. Correlations between numeric independent variables in the regression model were tested using Pearson's correlation test.

- Group size: It was calculated as the number of different PURs within each AWM unit on the CRB citrus layer, which was compared with the number of PURs routinely collected by the grower liaisons and found to be highly correlated (ρ=0.72, P=2E-15).
- Size of the resource system: It was calculated by aggregating all of the citrus properties in each PMA/PCD and calculating the sum of the grove acres. The calculated total citrus acreage under each management unit was highly correlated with data provided by the grower liaisons (ρ=0.97, P<2.2E-16) and with the citrus acreage recorded in the California Statewide Crop Mapping database (ρ=0.98, P<2.2E-16) (Department of Water Resources 2020).
- Size of citrus groves: It was calculated with the "Dissolve" tool from the software ArcGIS Pro by aggregating all of the citrus properties in each PMA/PCD and calculating the mean of the grove acres.

- Heterogeneity in grove size: It was calculated with the "Dissolve" tool from the software ArcGIS Pro by aggregating all of the citrus properties in each PMA/PCD and calculating the standard deviation of the grove acres.

Some preliminary statistical analyses were conducted to guide the hypotheses tested with the zoib regression model.

- Institutional approach (PMA/PCD): there was significantly higher participation in AWM in PCDs than PMAs in every season ($P \leq 0.043$ on t-tests), except the Fall of 2016 ($P=0.99$).
- Group size: there was a significant negative correlation between the number of pesticide use permits and participation in AWM ($\rho=-0.28$, $P<2.2E\text{-}16$).
- Size of citrus groves: there was a significant positive correlation between the average size of citrus groves and participation in AWM ($\rho=0.27$, $P \leq 2.2E\text{-}16$).

Zero-and-one-inflated beta regression models were constructed using the R package "zoib" (Liu and Kong 2015). A zoib model assumes that the dependent variable y (the percentage of citrus acreage in each PMA/PCD treated within the recommended window) follows a piecewise distribution such that

$$f(y_i) = \begin{cases} p_i & \text{if } y_i = 0 \\ (1-p_i)q_i & \text{if } y_i = 1 \\ (1-p_i)(1-q_i)\mathrm{Beta}(\alpha_{i1}, \alpha_{i2}) & \text{if } y_i \in (0,1) \end{cases}$$

where p_i represents the probability $\Pr(y_i=0)$, q_i represents the conditional probability $\Pr(y_i=1|y_i\neq 0)$, and α_{1i} and α_{2i} represent the shape parameters of the beta distribution for $y_i \in (0,1)$. These distributions are combined to derive the unconditional estimate of the response $E(y_i)$:

$$E(y_i) = (1-p_i)(\, q_i + (1-q_i)\mu_i^{(0,1)}$$

The zoib regression model estimates the logit [*i.e.*, the log(odds)] of the expected value of the beta distribution, the logit of $P(0)$ and $P(1)$ and the log of the dispersion of the beta distribution as linear functions of fixed and/or random effects. The coefficients of the effects on the mean of the beta regression can be interpreted as the expected change in the logit of participation with a one unit change in the corresponding variable. The coefficients of the effects on P(0) and P(1) are interpreted as the change in the logit of either having Participation=0 or Participation=1 with a one unit change in the corresponding variable. The coefficients of the effects on the dispersion of the beta distribution indicate the change in the log of the dispersion with a one-unit change in the corresponding variable (van Woerden et al. 2019). Based on a Bayesian framework, the coefficients are estimated through a Markov Chain Monte Carlo (MCMC) approach (Liu and Kong 2015). Two independent MCMC chains were run per model, each with 5000 iterations, including 200 iterations for burn-in, and thinned by a factor of 2. We assumed a Normal prior distribution N(0, 0.001) for each regression coefficient.

MCMC convergence was visually checked with trace plots and autocorrelation plots. The potential scale reduction factor (psrf) was calculated for each model parameter and the threshold psrf≤1.1 was used to determine that convergence had been reached (Gelman et al. 2021). In cases where psrf>1.1, we repeated the MCMC process with three chains, 10000 iterations per chain, 1000 for burn-in and thinned by a factor of 50. Posterior inferences for each parameter are reported as the mean and 95% credible interval (CI). Model selection was based on the deviance information criterion (DIC) (Liu and Kong 2015). Starting with the most complex model including the seven independent variables mentioned in the previous section, we examined the results and iteratively removed variables for which the CI of the posterior estimates was bounded by a negative and a positive value, and therefore comprised zero. Among competing models that fulfilled the previous condition, we chose the one with the lowest DIC (Table A4.1, Table A4.2).

Finally, the participation levels predicted by the zoib regression model were calculated using the pred.zoib function in the R package "zoib" (Liu and Kong 2015). Predictions were based on a new dataset where the independent variable under evaluation was allowed to vary within the range observed in the original dataset and the rest of the independent variables were fixed at their mean value, except in the case of interaction terms, where both variables were allowed to vary within the observed range.

All data sets and R code used in this study will be posted in a repository at the following URL after publication of this manuscript: https://github.com/nmcr01?tab=repositories.

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Appendix 3: Supplementary figures and tables

Table A3.1: Institutions coordinating area-wide management of ACP in Southern California.

County	Institution	History	Citrus acreage	Assessment rate (2018)	Coordinated treatments	Number of management units	Using PMAs?	Participation in AWM	Challenges	Other activities
Imperial	Imperial County Citrus Pest Control District	Formed in 1972 for California red scale (*Aonidiella aurantii*) control[†]. Expanded in 2013 to the whole county for ACP and HLB control[‡]	7,200	$15 / acre	Fall (Aug-Oct, Winter (Dec-Jan), Spring (Feb-Apr)	7 (6 after 2020)	No, PCD growing zones	High	ACP from across the Mexican border	Outreach, trap monitoring, coordination with Mexican authorities
Riverside	Citrus Pest Control District No. 2 (Coachella Valley)	Formed in 1946 for California red scale control[§]	8,000	$150 / acre	Fall (Sep-Oct), Winter (Dec-Jan)	4	No, four zones	High, reimbursing for treatments	Reinfestation from residential areas	Tree removal, biocontrol
	Citrus Pest Control	Formed in 2017 for ACP and	2,134	$100/acre	Fall (Sep), Winter (Dec-Jan)	2	No, two zones	Very high, three growers.	Reinfestation from	Funding some activities in

	District No. 3 (Hemet)	HLB control						Reimbursing for treatments	residential areas	residential areas
	Rest of the county	No entity directing the sprays	1,500	None	Fall, Winter			Low, not tracked	Absentee owners, small growers	UC Riverside promoting participation
San Bernardino	San Bernardino ACP/HLB Task Force	Formed in 2014[‖]	3,000	None	Fall (Oct-Nov), Winter (Nov-Dec), Spring (May-Jul)	19	Yes	Variable	Small growers, scarcity of PCOs, urban interface, water supply, bad actors	Grower liaison in contact with homeowners, reporting abandoned trees
San Diego	San Diego County Citrus Pest Control District	Formed in 2017 for ACP and HLB control[#]	4,500	$180 / acre	Fall (Aug-Sep), Winter (Jan), Spring (May-Jun)	3	No, three areas (Borrego Springs, San Pasqual, Pauma/Pala Valley)	Variable when it was voluntary. Now higher because of assessment reimbursements	Problems with organic treatments, small growers	County authorities monitor abandoned trees and try to remove them
Santa Barbara	Advisory committee	Formed in 2015 for ACP and HLB control[¶]	4,425	None	Fall (Sep), Winter (Jan)	12 (11 after 2019)	No, treating by cities	High	Weather, small properties	

Ventura	Ventura ACP/HLB Task Force	Formed in 2010 for ACP and HLB control[††]	25,000	None	Fall (Jul-Sep + Sep-Nov), Winter (Jan-Mar), Spring (Apr-Jun)	50	Yes	High	Spraying equipment shortage, continuous harvest, weather, movement of fruit	Outreach campaign in residential areas, reporting system for abandoned trees

[†] Margo Sanchez, pers. comm.

[‡] Mark McBroom, pers. comm.

[§] Baker, B. P. 1988. Pest Control in the Public Interest: Crop Protection in California. *UCLA Journal of Environmental Law and Policy* 8(1):31–71

[|] Bob Atkins, pers. comm.

[¶] Cressida Silvers, pers. comm.

[#] SDCCPCD. 2021. About Us. https://sdccpcd.specialdistrict.org/about-us.

[††] John Krist, pers. comm.

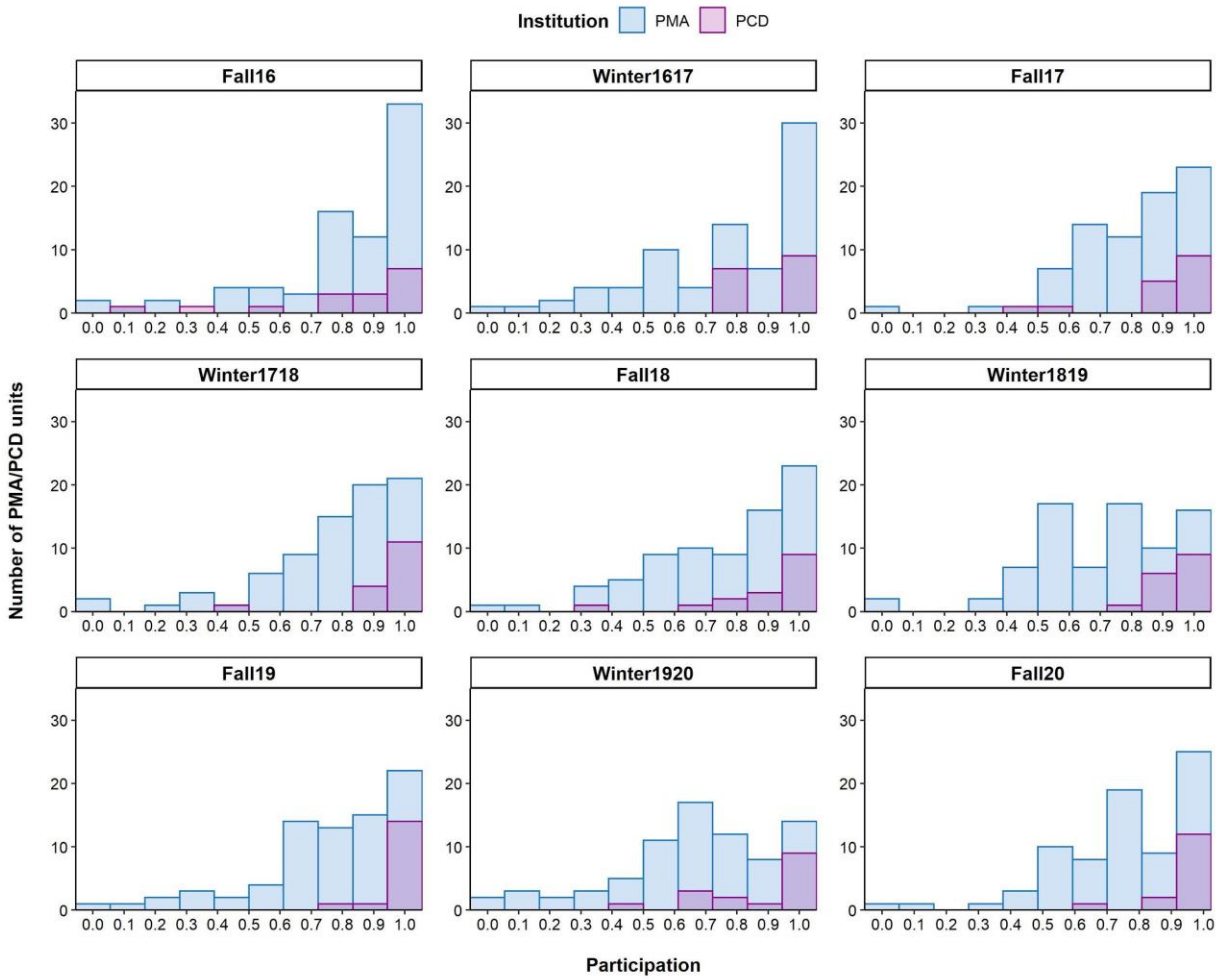

Fig. A3.1: Histogram of participation levels in area-wide management in Psyllid Management Areas (blue) and Pest Control Districts (purple) over nine seasons.

Table A3.2: Socio-economic characteristics of the survey respondents who indicated that they had citrus groves in Southern California (n =98).

Survey item	Responses
Role in citrus production	
Grove Owner	38
Ranch Manager	17
PCA	18
PCO	2
Other	18
NA	5
Farm size	
< 5 acres	23
5 – 25 acres	18
26 – 100 acres	11
101 – 500 acres	13
> 500 acres	28
NA	5
Age	
<35 years	12
35 - 50 years	14
51 – 65 years	37
> 65 years	35
Management system	
Conventional	59
Organic	13
Both	23
NA	3

Income from citrus	
< 25%	40
26 - 50%	13
51 - 75%	16
76 - 100%	23
NA	6

Note: Pest Control Adviser (PCA), Pest Control Operator (PCO), no answer (NA)

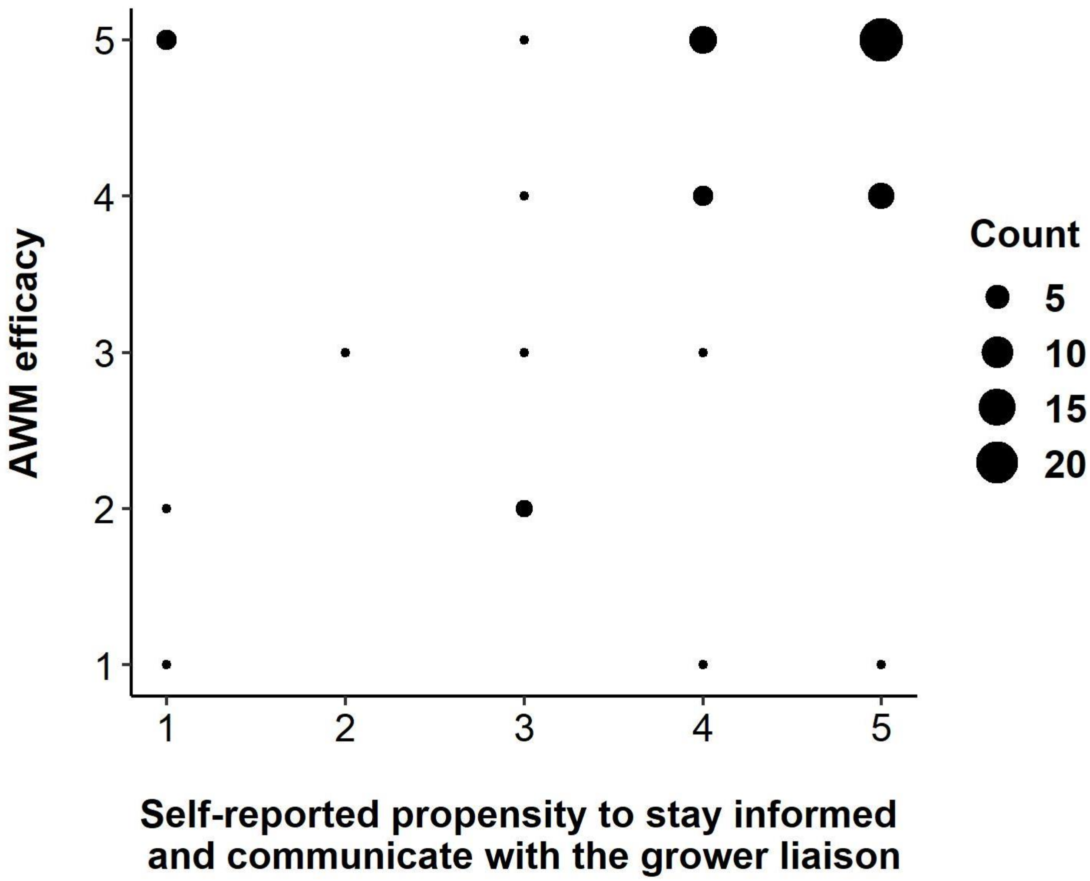

Fig. A3.2: Relationship between the self-reported propensity to stay informed and communicate with the grower liaison and the belief that coordinated insecticide treatments for ACP will slow down HLB spread more than uncoordinated treatments (AWM efficacy). Responses to the survey questions were transformed to numeric so that *very unlikely* = 1, *unlikely* = 2, *maybe* = 3, *likely* = 4, *very likely* = 5. The size of the points represents the number of participants who chose that combination of responses.

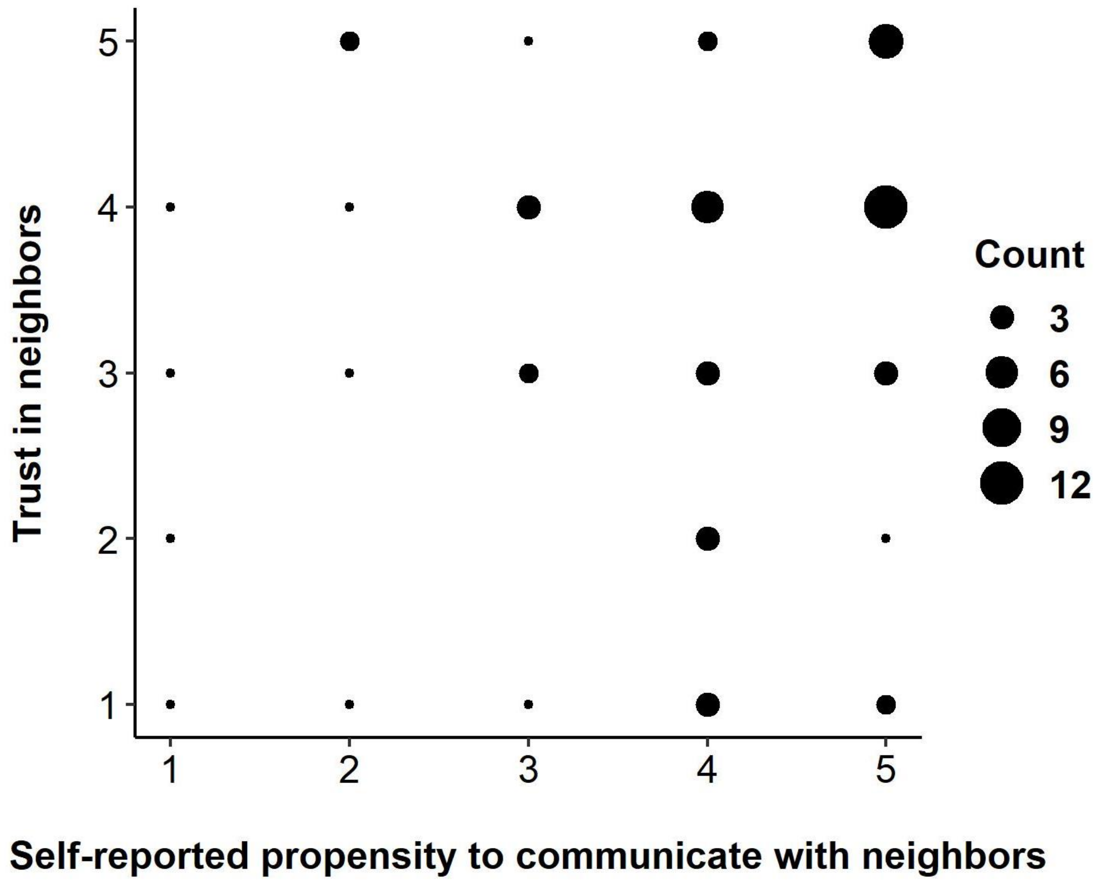

Fig. A3.3: Relationship between the self-reported propensity to communicate with neighbors and the belief that neighbors will apply insecticides for ACP within the recommended treatment window (trust in neighbors). Responses to the survey questions were transformed to numeric so that *very unlikely* = 1, *unlikely* = 2, *maybe* = 3, *likely* = 4, *very likely* = 5. The size of the points represents the number of participants who chose that combination of responses

Table A3.3: Posterior mean and 95% credible interval for the parameters in the zoib regression models evaluated that were more complex than the selected model (SD28).

		SD22 mean	SD22 2.5%	SD22 97.5 %	SD23 mean	SD23 2.5%	SD23 97.5 %	SD24 mean	SD24 2.5%	SD24 97.5 %	SD19 mean	SD19 2.5%	SD19 97.5 %	SD28 mean	SD28 2.5%	SD28 97.5 %
logit (mean)	Institutional approach†	-1.08	-1.67	-0.52	-1.08	-1.61	-0.53	-1.06	-1.63	-0.50	-0.68	-1.21	-0.13	-1.09	-1.65	-0.57
	Group size	-0.01	-0.02	0.00	-0.01	-0.02	0.00	-0.01	-0.02	0.00	-0.01	-0.02	-0.01	-0.01	-0.02	0.00
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Grove size	0.10	0.06	0.14	0.10	0.07	0.14	0.10	0.06	0.15	0.08	0.04	0.12	0.10	0.06	0.14
	Heterogeneity	0.08	0.05	0.12	0.09	0.05	0.12	0.09	0.05	0.12	0.12	0.08	0.15	0.08	0.05	0.12
	Season‡	-0.18	-0.32	-0.04	-0.17	-0.30	-0.04	-0.17	-0.29	-0.03	-0.16	-0.29	-0.03	-0.17	-0.30	-0.05
	Age	-0.07	-0.10	-0.04	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05
	Institution† x Age	0.17	0.10	0.25	0.17	0.09	0.25	0.17	0.09	0.25	0.18	0.09	0.26	0.17	0.10	0.25
	Grove size x Heterogeneity	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00
	Intercept	0.43	0.06	0.78	0.40	0.07	0.73	0.42	0.07	0.77	0.46	0.12	0.81	0.43	0.11	0.79
log(dispersion)	Institutional approach†	-0.81	-1.32	-0.30	-0.81	-1.32	-0.33	-0.80	-1.30	-0.31				-0.81	-1.30	-0.38
	Group size	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.03	0.04	0.03	0.02	0.04
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00
	Grove size	0.06	0.02	0.11	0.06	0.02	0.11	0.06	0.01	0.10				0.06	0.02	0.10
	Heterogeneity	-0.05	-0.09	-0.01	-0.05	-0.09	-0.02	-0.05	-0.09	-0.01				-0.05	-0.08	-0.02

	Season‡	-0.07	-0.27	0.13												
	Age	0.00	-0.03	0.04												
	Intercept	0.90	0.56	1.27	0.88	0.60	1.15	0.89	0.60	1.17	1.07	0.91	1.23	0.88	0.62	1.13
logit(P(1))	Institutional approach†	-92.64	-221.71	-6.68	-34.93	-85.72	-3.62	-46.39	-119.37	-3.70				-67.45	-188.90	-4.66
	Group size	-0.69	-1.21	-0.29	-0.61	-1.01	-0.31	-0.59	-1.07	-0.28	-0.49	-0.87	-0.22	-0.58	-0.93	-0.30
	Size of resource system	0.00	0.00	0.00												
	Grove size	-0.02	-0.15	0.10												
	Heterogeneity	0.04	-0.12	0.19							-0.01	-0.13	0.10			
	Season‡	0.51	-0.86	1.85												
	Age	-0.13	-0.40	0.13												
	Intercept	-1.06	-3.25	0.93	-1.37	-2.35	-0.43	-1.41	-2.45	-0.37	-2.13	-3.42	-0.96	-1.43	-2.38	-0.51
logit(P(0))	Institutional approach†	-0.22	-0.91	0.49												
	Group size	-0.31	-0.39	-0.24	-0.30	-0.37	-0.24	-0.32	-0.39	-0.26	-0.28	-0.34	-0.23	-0.32	-0.38	-0.27
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
	Grove size	0.08	0.04	0.13	0.08	0.04	0.13	0.05	0.02	0.08	0.07	0.05	0.10			
	Heterogeneity	-0.05	-0.11	0.00	-0.05	-0.10	0.00							0.03	0.00	0.06
	Season‡	-0.36	-0.82	0.08												
	Age	-0.08	-0.17	0.00												
	Intercept	0.50	-0.27	1.30	-0.13	-0.74	0.46	-0.20	-0.77	0.36	-0.34	-0.91	0.22	0.54	0.10	1.04
	DIC	1679813			1679811			1679814			1679852			1679849		

Multivariate psrf	1.39	1.05	1.20	1.01	1.10

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

Table A3.4: Posterior mean and 95% credible interval for the parameters in the zoib regression models evaluated that were less complex than the selected model (SD28).

		SD27	SD27	SD27	SD29	SD29	SD29	SD30	SD30	SD30	SD31	SD31	SD31	SD13	SD13	SD13	SD21	SD21	SD21	SD0	SD0	SD0
		mean	2.5%	97.5%	mean	2.5%	97.5%	mean	2.5%	97.5%	mean	2.5%	97.5%	mean	2.5%	97.5%	mean	2.5%	97.5%	mean	2.5%	97.5%
logit (mean)	Institutional approach†	-1.08	-1.64	-0.51	-1.34	-1.89	-0.83	-0.24	-0.68	0.20	-0.54	-0.97	-0.13	-0.67	-1.17	-0.13	-0.58	-1.13	-0.03			
	Group size	-0.01	-0.02	0.00	-0.02	-0.02	-0.01	-0.01	-0.02	0.00	-0.02	-0.02	-0.01	-0.01	-0.02	-0.01	-0.02	-0.03	-0.01			
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Grove size	0.10	0.07	0.14	0.03	0.00	0.06	0.10	0.06	0.14	0.03	0.00	0.05	0.08	0.04	0.12	0.09	0.05	0.12			
	Heterogeneity	0.08	0.04	0.12	0.02	-0.01	0.05	0.08	0.05	0.12	0.02	-0.01	0.05	0.12	0.08	0.15	0.13	0.09	0.16			
	Season‡	-0.17	-0.29	-0.04	-0.15	-0.28	-0.02	-0.17	-0.30	-0.04	-0.15	-0.28	-0.03	-0.16	-0.29	-0.03	-0.16	-0.30	-0.02			
	Age	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05	-0.06	-0.08	-0.03	-0.06	-0.08	-0.03	-0.07	-0.10	-0.05	-0.07	-0.10	-0.04			
	Institution† x Age	0.17	0.09	0.25	0.16	0.08	0.24							0.18	0.09	0.26	0.17	0.08	0.26			
	Grove size x Heterogeneity	-0.01	-0.01	0.00				-0.01	-0.01	0.00				-0.01	-0.01	0.00	-0.01	-0.01	0.00			

	Intercept	0.41	0.07	0.76	1.05	0.79	1.30	0.34	-0.01	0.69	0.96	0.71	1.23	0.47	0.12	0.81	0.51	0.17	0.86	1.06	0.98	1.15
log (dispersion)	Institutional approach†	-0.82	-1.32	-0.33	-0.88	-1.38	-0.40	-0.89	-1.38	-0.41	-0.95	-1.44	-0.44									
	Group size	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.03	0.04						
	Size of resource system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00									
	Grove size	0.06	0.02	0.11	0.06	0.02	0.10	0.07	0.03	0.11	0.07	0.03	0.11									
	Heterogeneity	-0.05	-0.09	-0.02	-0.06	-0.10	-0.02	-0.06	-0.09	-0.02	-0.06	-0.10	-0.03									
	Season‡																					
	Age																					
	Intercept	0.88	0.60	1.16	0.87	0.60	1.16	0.87	0.59	1.14	0.87	0.59	1.14	1.07	0.91	1.23	1.53	1.42	1.63	1.24	1.14	1.34
logit (P(1))	Institutional approach†																					
	Group size	-0.47	-0.83	-0.23	-0.48	-0.89	-0.23	-0.47	-0.84	-0.22	-0.51	-0.91	-0.24	-0.49	-0.85	-0.22						
	Size of resource system																					
	Grove size																					
	Heterogeneity																					
	Season‡																					
	Age																					
	Intercept	-2.22	-3.12	-1.36	-2.17	-3.10	-1.31	-2.21	-3.12	-1.35	-2.14	-3.06	-1.27	-2.17	-3.10	-1.30	-4.37	-5.00	-3.79	-4.37	-5.03	-3.79
logit (P(0))	Institutional approach†																					
	Group size	-0.32	-0.38	-0.27	-0.32	-0.38	-0.26	-0.32	-0.38	-0.26	-0.32	-0.38	-0.26	-0.31	-0.37	-0.26						
	Size of resource system																					

Grove size																					
Heterogeneity	0.03	0.00	0.07	0.03	0.00	0.07	0.03	0.00	0.07	0.03	0.00	0.07									
Season‡																					
Age																					
Intercept	0.53	0.06	1.01	0.53	0.05	1.00	0.53	0.05	1.02	0.53	0.05	1.03	0.89	0.55	1.25	-1.43	-1.61	-1.25	-1.43	-1.60	-1.26
DIC	1679860			1679885			1679877			1679900			1679883			1680225			1680402		
Multivariate psrf	1.04			1.02			1.05			1.05			1.02			1.05			1		

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

Table A3.5: Posterior mean and 95% credible interval for the parameters in the selected zoib regression model (SD28) with the size of the resource system, and the model without this independent variable (SD32).

		SD28 mean	SD28 2.5%	SD28 97.5%	SD32 mean	SD32 2.5%	SD32 97.5%
logit(mean)	Institutional approach†	-1.09	-1.65	-0.57	-0.65	-1.17	-0.13
	Group size	-0.01	-0.02	0.00	-0.01	-0.01	0.00
	Size of resource system	0.00	0.00	0.00			
	Grove size	0.10	0.06	0.14	0.13	0.09	0.16
	Heterogeneity	0.08	0.05	0.12	0.10	0.07	0.13
	Season‡	-0.17	-0.30	-0.05	-0.17	-0.31	-0.04
	Age	-0.07	-0.10	-0.05	-0.07	-0.10	-0.05
	Institution† x Age	0.17	0.10	0.25	0.17	0.09	0.26
	Grove size x Heterogeneity	-0.01	-0.01	0.00	-0.01	-0.01	-0.01
	Intercept	0.43	0.11	0.79	0.26	-0.06	0.58
log(dispersion)	Institutional approach†	-0.81	-1.30	-0.38	-0.42	-0.82	0.01
	Group size	0.03	0.02	0.04	0.04	0.03	0.05
	Size of resource system	0.00	0.00	0.00			
	Grove size	0.06	0.02	0.10	0.07	0.03	0.11
	Heterogeneity	-0.05	-0.08	-0.02	-0.05	-0.08	-0.02
	Season‡						
	Age						

	Intercept	0.88	0.62	1.13	0.88	0.62	1.15
logit(P(1))	Institutional approach†	-67.45	-188.90	-4.66	-53.65	-126.63	-3.99
	Group size	-0.58	-0.93	-0.30	-0.58	-0.94	-0.30
	Size of resource system						
	Grove size						
	Heterogeneity						
	Season‡						
	Age						
	Intercept	-1.43	-2.38	-0.51	-1.42	-2.39	-0.47
logit(P(0))	Institutional approach†						
	Group size	-0.32	-0.38	-0.27	-0.32	-0.37	-0.27
	Size of resource system						
	Grove size						
	Heterogeneity	0.03	0.00	0.06	0.03	0.00	0.07
	Season‡						
	Age						
	Intercept	0.54	0.10	1.04	0.54	0.06	1.04
	DIC	1679849			1679861		
	Multivariate psrf	1.10			1.33		

Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

† Institutional approach was modeled as a factor, considering PMA as the baseline

‡ Season of treatment was modeled as a factor, considering Fall as the baseline

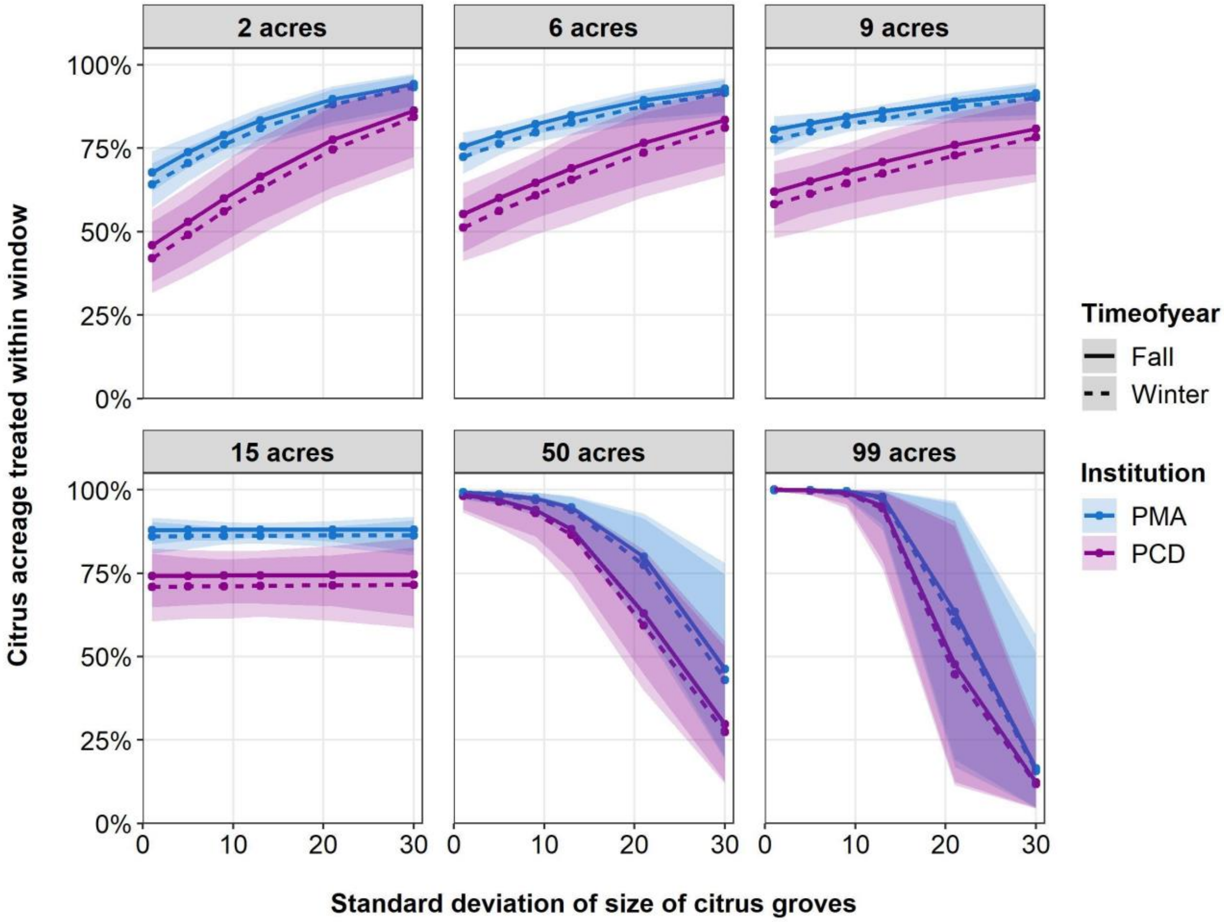

Fig. A3.4: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 1 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

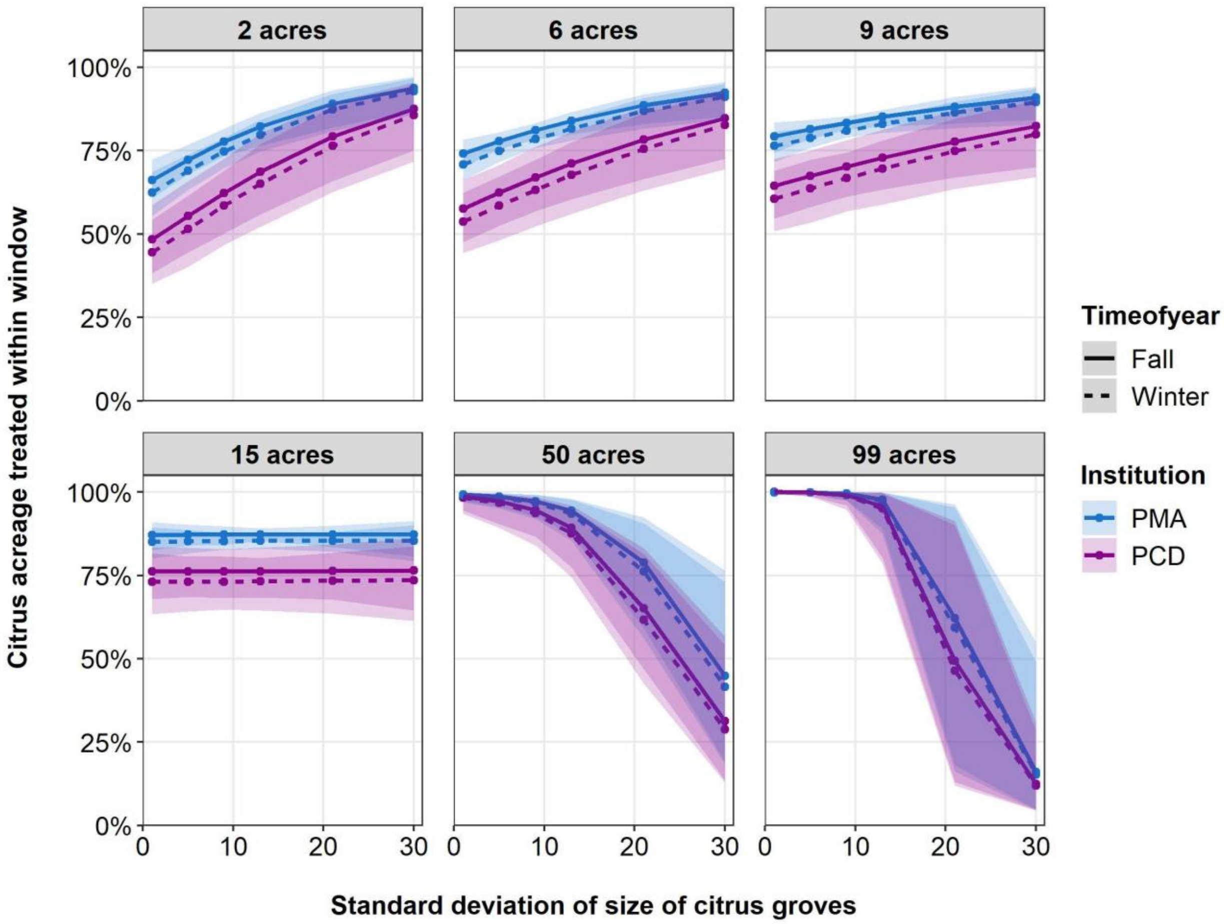

Fig. A3.5: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 2 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

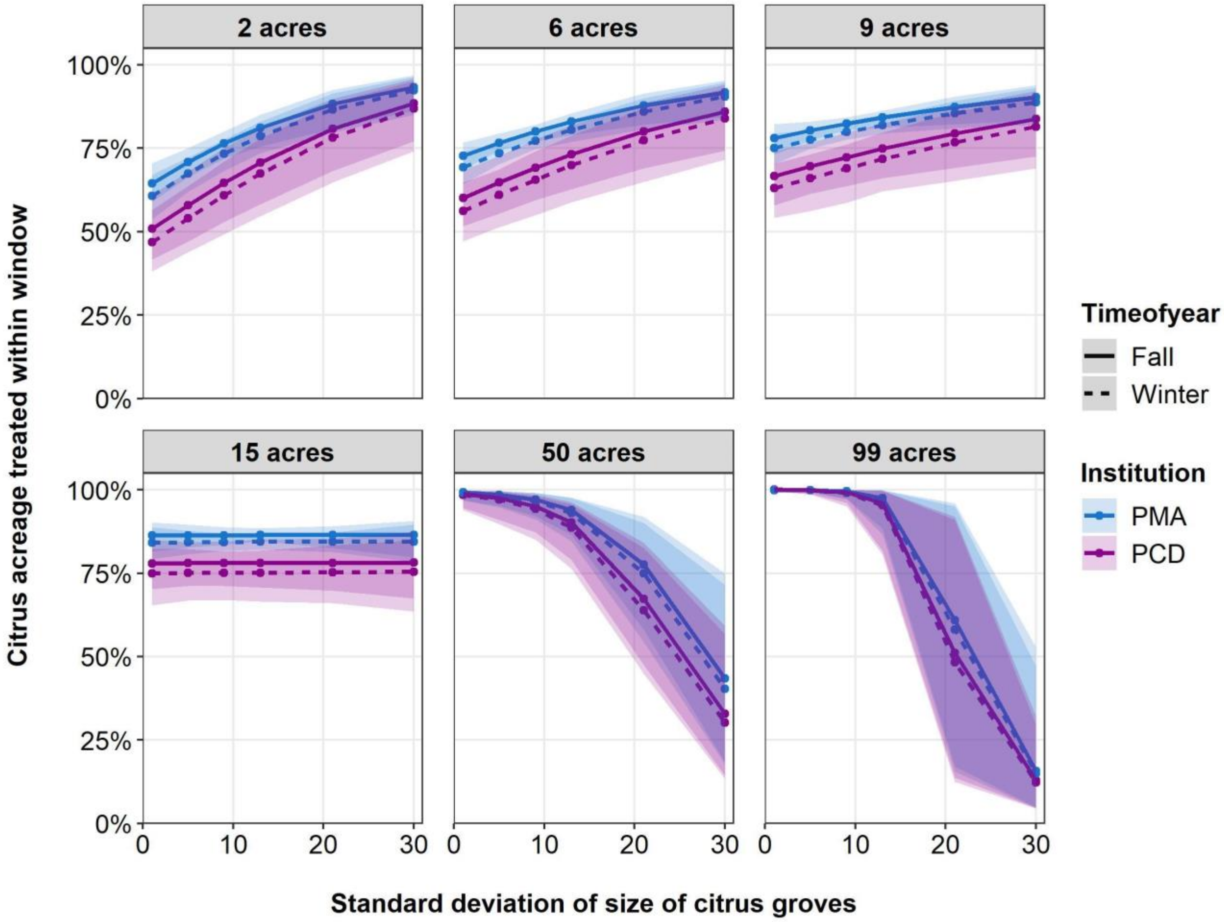

Fig. A3.6: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 3 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

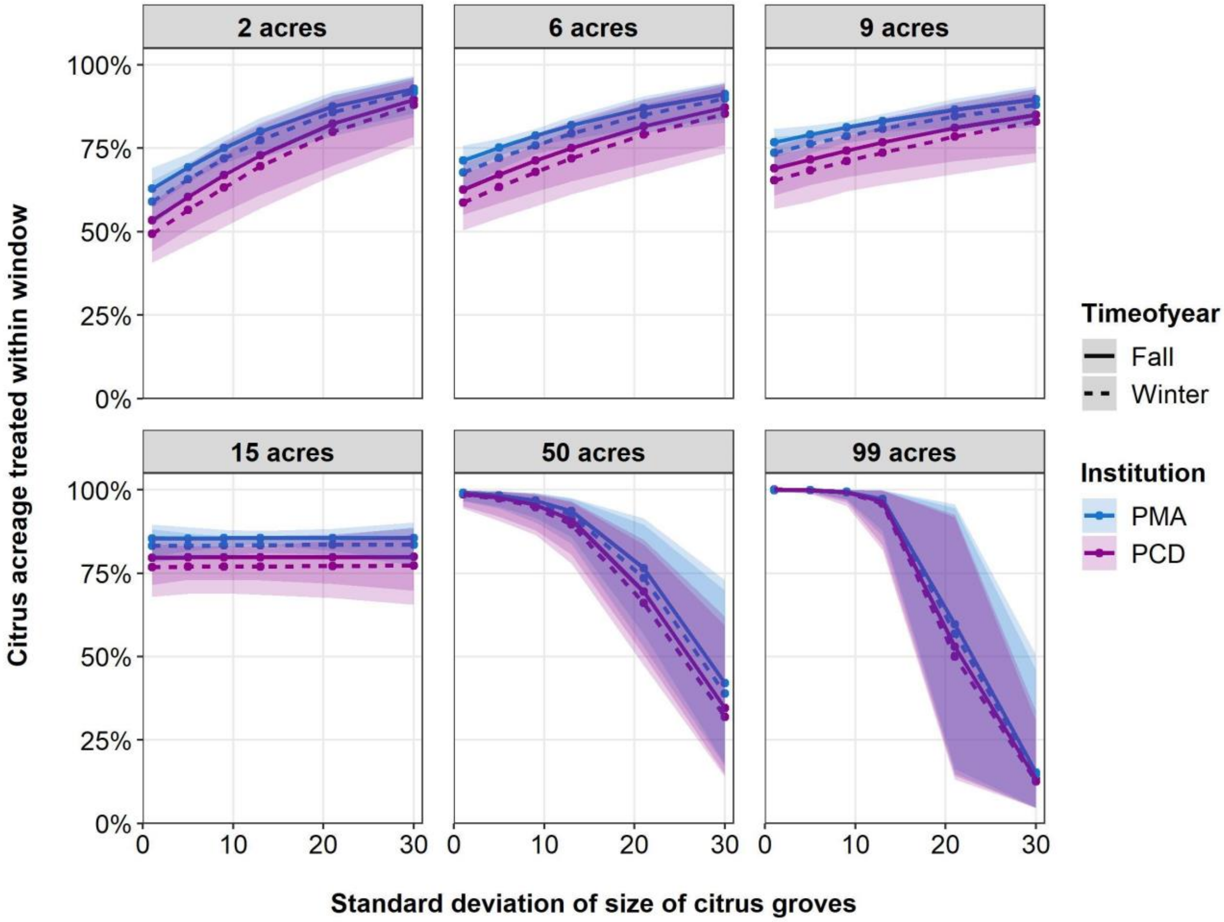

Fig. A3.7: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 4 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

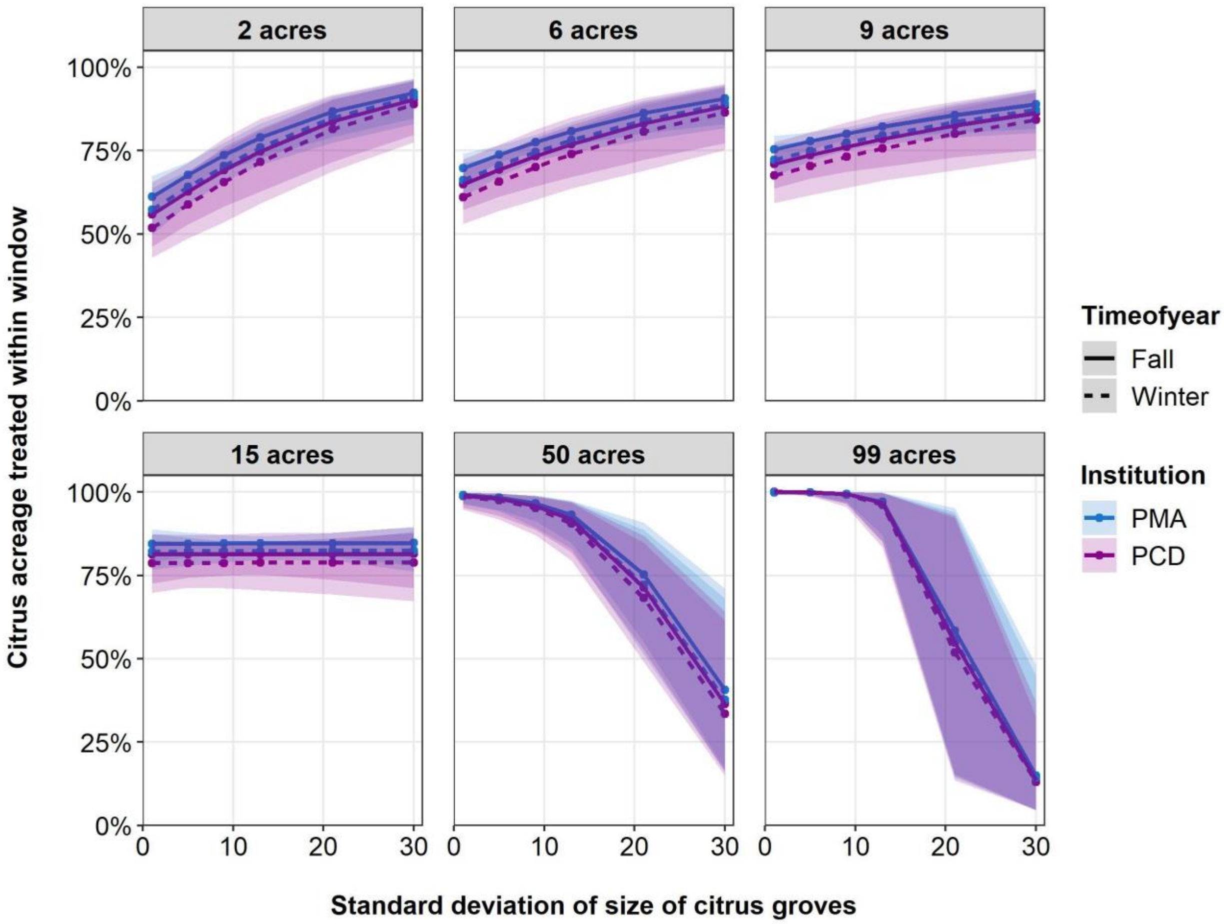

Fig. A3.8: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 5 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

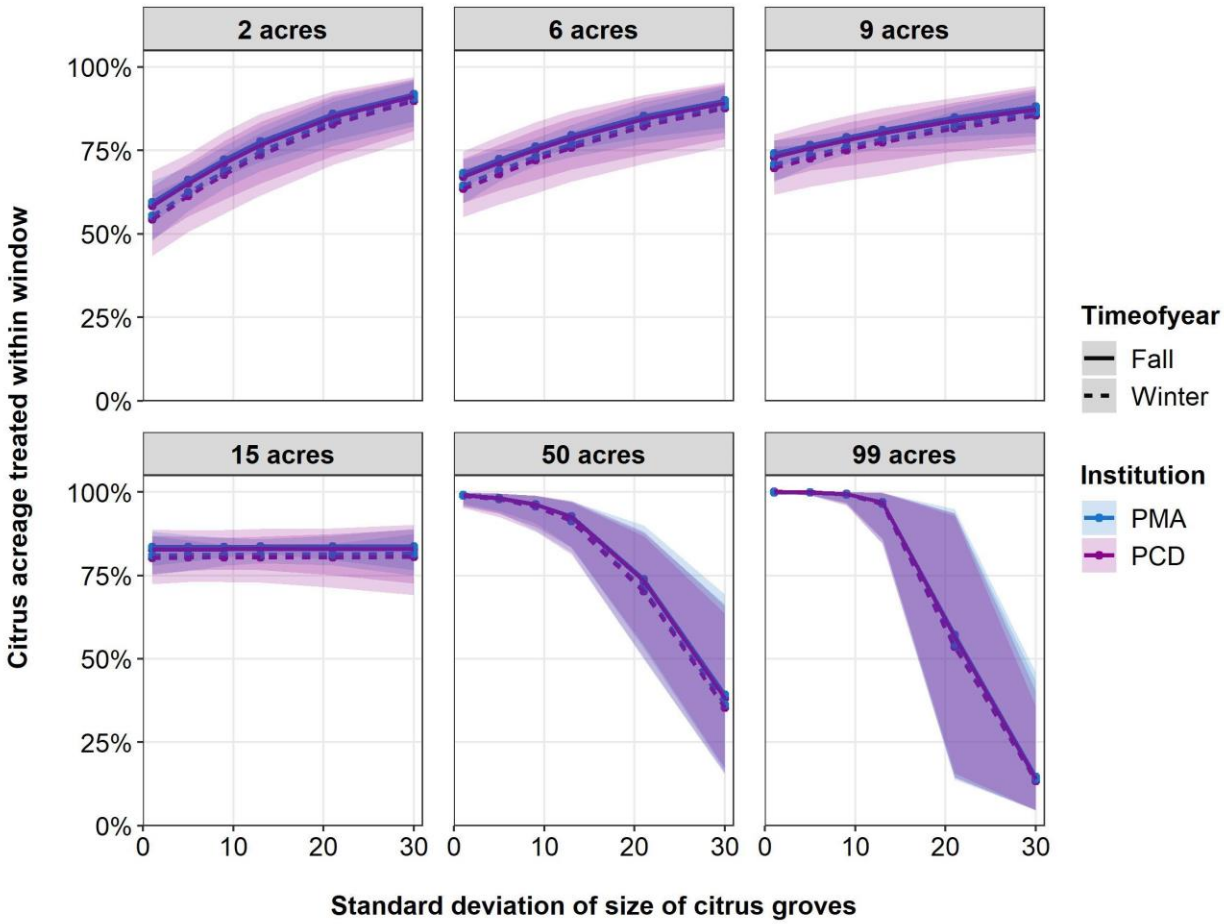

Fig. A3.9: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 6 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

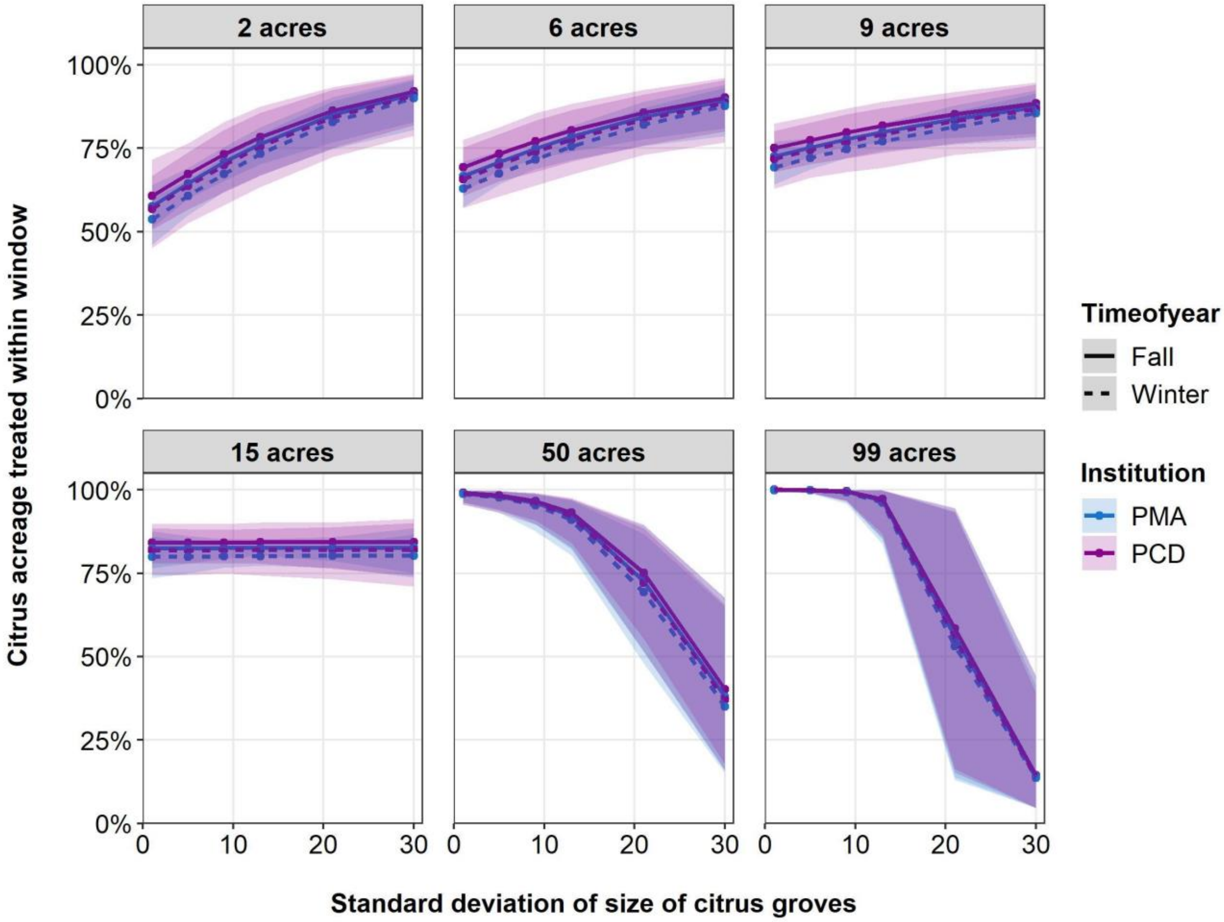

Fig. A3.10: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 7 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management unit.

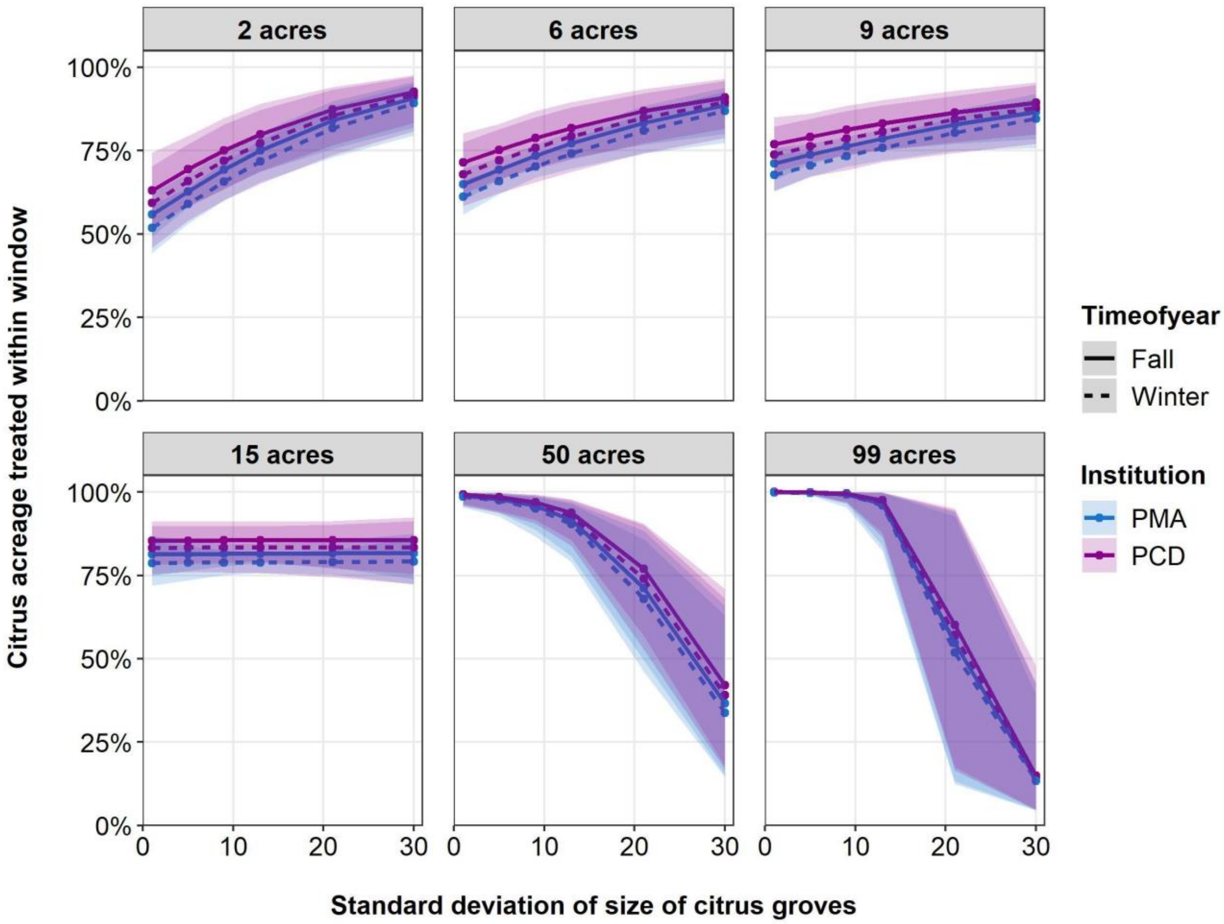

Fig. A3.11: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 8 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values for the winter treatments are linked by dashed lines. The panels show different average sizes of the citrus groves in a management

Citrus Pest & Disease Prevention Program: Exhibits for Virtual Hearings

Annual Report:

- FY 2017-2018 Annual Report: https://citrusinsider.org/annual-report-2018/
- FY 2019-2020 Annual Report: https://citrusinsider.org/annual-report-2020/

Media Coverage:

- La Opinion: An infestation puts California oranges at risk. How to fight it from home.
- The Mercury News: Tiny helpful wasps are coming to save your citrus
- Bakersfield Californian: Spike in pest detections threatens Kern County's citrus; residents and growers must gear up for the fight
- NBC San Diego: Tiny Wasps Being Released Across San Diego… For Good Reason
- CBS Los Angeles: 'Beneficial Wasps' Released Across Southern California To Prey On Pest Spreading Disease To Citrus Trees
- San Diego Union-Tribune: Citrus tree HLB disease found close to San Diego
- Orange County Breeze: Residents urged against moving citrus material this summer due to harmful citrus tree disease
- NBC Los Angeles: Contaminated Fruit and Trees — What to Look for With Citrus Disease This Summer
- The Press-Enterprise: Replacing underperforming Redlands orange groves with lemons could be a gamble
- Orange County Register: Orange County citrus at a crossroad
- Bakersfield Now: To stop spread of pest, Californians are asked to remove leaves before transporting citrus
- Los Angeles Daily News: Want to help fight citrus greening disease? Take the leaves off that orange before sharing it
- The Fresno Bee: Citrus disease could kill California industry if Congress slows research, growers warn
- Ag Net West: California's Positive Progress: A Sign to Keep Moving Forward in the Fight Against HLB
- Ag Net West: Data Shows that Citrus Tarping Having Positive Impact on ACP Movement
- AgriPulse: In combating citrus greening and its insect host, California has a leg up
- Citrus Industry Magazine: California HLB Detections Increased in 2018 as Monitoring Efforts Intensified
- Western Farm Press: Citrus farms prepare for HLB's arrival
- Capital Press: Industry Committee Endorses Voluntary Best Practices for Citrus Growers' Response to Huanglongbing
- Ag Daily: California puts together strategic plan to fight Huanglongbing

Program Successes:

- DATOC finds regulated tarping practices to be successful in reducing ACP movement
- UC/CRB study examines growers' adoptability of voluntary best practices

- California’s Successful HLB Management Strategy Focuses on Everyone Doing Their Part
- Voluntary Grower Response Plan for Huanglongbing
- CPDPP’s Strategic Plan (2018)

BEST PRACTICES IN RESPONSE TO HUANGLONGBING IN CALIFORNIA CITRUS

UPDATED JUNE 10, 2019

PURPOSE

The following voluntary grower actions were endorsed by the Citrus Pest & Disease Prevention Committee on May 29, 2019 in order to provide California citrus growers recommended best practices for responding to a nearby CLas detection (the bacterium that is associated with Huanglongbing (HLB) beyond the required regulatory response. The recommendations represent the most effective tools known to the citrus industry at this time, and growers are encouraged to use as many methods as are feasible for their operation in order to limit the spread of the Asian citrus psyllid (ACP) and HLB, as the cost to manage the Asian citrus psyllid is far less than any potential costs or loss to the industry should HLB take hold throughout our state.

CONTENTS

FUTURE UPDATES

The suggested actions listed in this toolkit will be actively updated and modified as conditions warrant, or as new information, data and tools become available. For example, Early Detection Technologies (EDTs) are under development, and as they become available and growers gain confidence in them, they should be used to determine which trees are in the early stages of CLas infection.

CDFA REGULATORY RESOURCES

The following recommendations are supplemental to the CDFA regulatory response to an HLB-positive tree or a CLas-infected ACP. Details on CDFA's response can be found at https://tinyurl.com/CDFAProtocol

Mitigations required to move bulk citrus between ACP or HLB quarantine zones can be found at https://tinyurl.com/hlbmitigations

BRIEF DEFINITION OF TERMINOLOGY

Candidatus Liberibacter asiaticus (CLas): Bacteria that are associated with huanglongbing (HLB) or citrus greening in many citrus-producing areas around the world.

Asian Citrus Psyllid (ACP): An insect that can transmit CLas. It is considered invasive in California.

Huanglongbing (HLB): Also known as citrus greening, HLB is the most devastating disease of citrus plants worldwide. In California, it is spread by CLas-infected Asian citrus psyllids (ACP) . HLB was formerly known as citrus greening.

PCR: A biochemical test used to determine if a tree or psyllid contains CLas.

EDT: Early Detection Technology; any test that detects CLas sooner than PCR.

EXPLANATION OF AREAWIDE ACP TREATMENT PROGRAM

The Areawide ACP Treatment Program is an organized, coordinated insecticide treatment among neighboring orchards with the goal of achieving greater psyllid control than if the orchards were treated individually at different times. Insecticide treatments are applied during the winter (Dec–Jan) and again in the late summer and fall months (1–2 treatments, depending on the region, in Jul–Aug and Sep–Oct). Carefully comply with application instructions to ensure chemical effectiveness. Growers should work closely with their local PCD/Task Force regarding treatment timing and review the UC IPM Guidelines for Citrus for the choice of insecticide. Additional treatments should be applied by growers when psyllid populations increase between the coordinated treatments. Perimeter treatments in mature orchards can be used in Scenario 1 (see below) if the borders have low ACP densities (<0.5 nymph/flush) and the center of the orchard is demonstrated to be free of psyllids. Young orchards and orchards where ACP are not aggressively managed must be sprayed in their entirety.

- Two fall treatments are recommended for Ventura, Santa Barbara, San Bernardino and central Riverside.
- One fall treatment is recommended for Coachella, Temecula, San Diego and Imperial.
- Two organic treatments are applied for every conventional treatment.

RECOMMENDATIONS

These recommendations for psyllid and HLB control are designed for regions of Southern California where ACP are well-established and areawide management programs are in progress, which includes Santa Barbara, Ventura, Riverside, San Bernardino, San Diego, Orange and Imperial counties.

The San Joaquin Valley, the northern coast and inland areas are still using a local eradication strategy and ACP are not well-established. In these regions, growers are reminded to stay aware of the situation by participating in seminars and communicating with grower liaisons, scouting for psyllids, complying with coordinated treatments, using ACP effective insecticides for treatments, and supporting efforts to locally eradicate psyllids. The situation in the central and northern regions could change and, if so, the areawide scenarios would then apply. As mentioned above, the best practices listed will be actively updated and modified as conditions warrant.

The following recommendations are broken into four scenarios with different actions for each one.

Scenario 1	Orchards beyond the 5-mile quarantine.
Scenario 2	Orchards within the 5-mile quarantine, but farther than 1 mile from an HLB detection.
Scenario 3	Orchards within 1 mile of an HLB detection, but not known to be infected.
Scenario 4	PCR-positive plant material or a PCR-positive ACP is found in an orchard.

SCENARIO 1: ORCHARDS OUTSIDE A 5–MILE QUARANTINE

Recommended Actions

- ☐ **Awareness:** Communicate regularly with local Grower Liaisons, Cooperative Extension, Pest Control Districts (PCD), County Agricultural Commissioners (CAC), Pest Control Advisors (PCA), and others for the most up to date information and best practices. Get to know your neighbors, attend industry meetings and sign up for alerts on CitrusInsider.org to stay informed.
- ☐ **Scout for ACP Nymphs:** Deploy trained scouts to look for ACP every 2 weeks. Sample for nymphs by examining 10 tender flushes (1 per tree) on each of the four borders (first row or tree) and one row in the center of the orchard. Be extra vigilant in sampling young trees. Treatments are recommended when ACP are present and before they reach 0.5 nymphs/flush.
- ☐ **Control ACP with Insecticides:**
  - Participate in areawide treatment programs and strive to eliminate psyllids, or at least reduce their numbers below 0.5 nymphs per flush by applying winter and fall treatments. Apply additional treatments (within label limits) if populations start to increase before a scheduled areawide treatment.
  - Treat the border before the center of the orchard and, if possible, make applications at night when psyllids are inactive to avoid driving psyllids out of the orchard.
  - When treating for other pests, utilize insecticides known to have efficacy against ACP whenever possible.
  - According to University of California, conventional broad spectrum pyrethroid and several neonicotinoid insecticides have been shown to be most effective in controlling ACP because of their long residual life. If softer insecticides or oils are used for ACP management, increase the treatment frequency to every 2 weeks, when psyllids are present.
- ☐ **Young Trees/Replants:** Young citrus is highly attractive to ACP. When planting citrus, consider applying additional protectants (kaolin, insecticides) and/or cover the citrus trees with psyllid-proof mesh bags.
- ☐ **Barriers/Repellents:** Psyllids infest the edges of groves first and prefer the edge when their densities are low. Create barriers such as fencing with psyllid-proof screening or windbreaks to block ACP arrival and/or apply repellents to limit ACP establishment on the perimeter of the orchard. There may be regional differences in the suitability of these tactics.
- ☐ **Visual Survey for HLB:** Conduct a visual survey for HLB symptoms in the border row/trees and in the uppermost part of tree canopies by whatever means possible once a year, during late spring or late fall. Have any suspicious tissue tested via PCR.
- ☐ **Tree Health:** Ensure appropriate nutrient and water applications to tend to your orchard's leaf and root health.

SCENARIO 2: ORCHARDS BETWEEN 1 AND 5 MILES FROM AN HLB DETECTION

Recommended Actions

- ☐ **Awareness:** Communicate regularly with local Grower Liaisons, Cooperative Extension, Pest Control Districts (PCD), County Agricultural Commissioners (CAC), Pest Control Advisors (PCA), and others for the most up to date information and best practices. Attend citrus industry meetings to stay informed and sign up for alerts on CitrusInsider.org. Help educate your neighbors about the seriousness of the situation and be prepared to help with communications and spray applications.
- ☐ **Scout for ACP Nymphs:** Deploy trained scouts to look for ACP every 2 weeks. Sample for nymphs by examining 10 tender flushes (1 per tree) on each of the 4 borders (first row or tree) and 1 row in the center of the orchard. . Be extra vigilant in sampling young trees. If ACP are found, treat with insecticides before they reach 0.5 nymphs/flush in any area of the orchard.
- ☐ **Control ACP with Insecticides:**
  - Treat the entire orchard a minimum of 3 times per year (regional differences no longer apply) with an ACP-effective, long-residual insecticide (once in winter during Dec–Jan, and twice in fall during Jul–Aug and again from Sep–Oct). Coordinate with your liaison, PCD, and/or local Task Force for precise treatment timing.
  - Between the 3 minimum applications, apply additional insecticides (within label limits) before psyllids reach 0.5 nymphs/flush. These extra treatments can be applied to the perimeter of mature orchards if the center of the orchard is demonstrated to be free of psyllids.
  - Treat the border before the center of the orchard and, if possible, make applications at night when psyllids are inactive to avoid driving psyllids out of the orchard.
  - When treating for other pests, utilize insecticides known to have efficacy against ACP whenever possible.
  - According to University of California, conventional broad-spectrum pyrethroid and several neonicotinoid insecticides have been shown to be most effective in controlling ACP because of their long residual life. If softer insecticides or oils are used for ACP management, increase the treatment frequency to every 2 weeks.
- ☐ **Young Trees/Replants:** Young citrus is highly attractive to ACP. In young orchards, or when replanting citrus, apply additional protectants (such as kaolin or insecticides) and/or cover the citrus trees with psyllid-proof mesh bags. Young orchards should be treated in their entirety.
- ☐ **Barriers/Repellents:** Psyllids infest the edges of groves first and prefer the edge when their densities are low. Create barriers such as fencing or windbreaks to block ACP arrival and/or apply repellents to limit ACP establishment on the perimeter of the orchard. There may be regional differences in the suitability of these tactics.
- ☐ **Visual Survey for HLB:** Conduct a visual survey for HLB symptoms in the two border rows/trees and in the uppermost part of tree canopies by whatever means possible twice a year during late spring and late fall. Test any suspicious tissue via PCR.
- ☐ **Direct CLas Detection Protocol:** Test foliage and psyllids from 10 trees in each corner of the block (total 40 trees) using direct methods of detection of the bacterium using a laboratory permitted by CDFA or a commercial kit (such as PCR or ELISA-based kits).
- ☐ **Tree Health:** Ensure appropriate nutrient and water applications to maximize leaf and root health.
- ☐ **If HLB is Detected**: Grower voluntary response changes to scenario 4.

SCENARIO 3: ORCHARDS WITHIN 1 MILE OF AN HLB DETECTION, BUT NOT KNOWN TO BE INFECTED

Recommended Actions

- ☐ **Awareness and Coordinated Efforts:** Communicate regularly with local Grower Liaisons, Cooperative Extension, Pest Control Districts (PCD), County Agricultural Commissioners (CAC), Pest Control Advisors (PCA), and others for the most up to date information and best practices. Attend citrus industry meetings to stay informed and sign up for alerts on CitrusInsider.org. Help educate your neighbors about the seriousness of the situation and be prepared to help with communications and spray applications. Offer to lead your psyllid management area's communication network. HLB control needs to be a group effort — you can't do it on your own.
- ☐ **Scout for ACP:** Deploy trained scouts to look for ACP every 2 weeks. Sample for nymphs by examining 10 tender flushes (1 per tree) on each of the four borders (first row or tree) and 1 row in the center of the orchard. If ACP are found, treat before psyllids reach 0.5 nymphs/flush in any area of the orchard. Pay special attention to vigorously flushing trees and areas under high ACP pressure. For example, monitor where the orchard edges border residences or where ACP populations have been found in the past.
- ☐ **Control ACP with Insecticides:**
  - Treat the *entire* orchard a minimum of 3 *times per year* (regional differences no longer apply) with an ACP-effective, long-residual insecticide (once in winter from Dec–Jan, and twice in fall during Jul–Aug and during from Sep–Oct). Coordinate with your liaison for treatment timing.
  - Between the 3 minimum applications, apply additional insecticides (within label limits) before psyllids reach 0.5 nymphs/flush. Treat the whole orchard.
  - Treat the border before the center of the orchard and, if possible, make applications at night when psyllids are inactive to avoid driving psyllids out of the orchard.
  - When treating for other pests, utilize insecticides known to have efficacy against ACP whenever possible.
  - According to University of California, conventional broad spectrum pyrethroid and several neonicotinoid insecticides have been shown to be most effective in controlling ACP because of their long residual life. If softer insecticides (such as oils) are used, increase treatment frequency to every 2 weeks.
- ☐ **Young Trees/Replants:** Practice exclusionary treatments for young trees or replants such as ACP-proof mesh covers. Replant with tolerant or resistant rootstocks or scions as they become available.
- ☐ **Barriers/Repellents:** Psyllids infest the edges of groves first. Create barriers such as fencing with psyllid-proof screening or windbreaks to block ACP arrival and/or apply repellents to limit ACP establishment on the perimeter of the orchard. There may be regional differences in the suitability of these tactics.
- ☐ **Visual Survey for HLB:** Conduct a visual survey for HLB symptoms in the entire orchard, including the uppermost part of tree canopies by whatever means possible twice a year, during late spring and late fall. Test any suspicious tissue via PCR.

- ☐ **Direct CLas Detection Protocol:** Test foliage (and any psyllids found) from 100% of trees in the perimeter row/tree using direct methods of detection of the bacterium such as PCR. CDFA will test tree borders and psyllids within 400 meters of an HLB detection. Test additional trees through an approved laboratory or commercial kit (such as PCR or ELISA-based kits). Report any self-conducted positive test results from a direct method to CDFA, who will then take regulatory action.
- ☐ **Tree Health:** Ensure appropriate nutrient and water applications to maximize root health.
- ☐ **If Huanglongbing is detected:** Grower voluntary response changes to scenario 4.

SCENARIO 4: PCR-POSITIVE PLANT MATERIAL OR A PCR-POSITIVE ACP IS FOUND IN AN ORCHARD

Recommended Actions

- ☐ **Awareness:** Communicate regularly with local Grower Liaisons, Cooperative Extension, Pest Control Districts (PCD), County Agricultural Commissioners (CAC), Pest Control Advisors (PCA) and others for the most up to date information and best practices. Attend citrus industry meetings to stay informed and sign up for alerts on CitrusInsider.org. Help educate your neighbors about the seriousness of the situation and be prepared to help with communications and spray applications. Offer to lead your psyllid management area's communication network. HLB control needs to be a group effort — you can't do it on your own. Alert neighboring homeowners to organizations that assist homeowners with citrus tree removal.
- ☐ **Scout for ACP:** Deploy trained scouts regularly (every 2 weeks) to look for ACP. Sample flush for nymphs on border rows (first row or tree). Examine 10 flushes per border or center row. If ACP are found, treat *before* psyllids reach 0.5 nymphs/flush in any area of the orchard. Pay special attention to young and flushing trees, and areas under high ACP pressure. For example, monitor where the orchard borders residences or where ACP populations have been found in the past.
- ☐ **Control ACP with Insecticides:** **<u>Effective psyllid control is the most important tool to manage HLB spread.</u>**
  - Treat the *entire* orchard a minimum of 3 *times per year* (regional differences no longer apply) with an ACP-effective, long-residual insecticide (once in winter from Dec–Jan, and twice in fall from Jul–Aug and again from Sep–Oct). Coordinate with your liaison for treatment timing.
  - Between the 3 minimum applications, apply *additional* insecticides (within label limits), before psyllids reach 0.5 nymphs/flush. Treat the whole orchard.
  - Treat the border before the center of the orchard and, if possible, make applications at night when psyllids are inactive to avoid driving psyllids out of the orchard.
  - When treating for other pests, utilize insecticides known to have efficacy against ACP whenever possible.
  - According to University of California, conventional broad-spectrum pyrethroids and several neonicotinoid insecticides have been shown to be most effective in controlling ACP because of their long residual life. If softer insecticides (such as oils) are used, increase treatment frequency to every 2 weeks.
- ☐ **Young Trees/Replants:** Practice exclusionary treatments for young trees or replants, such as ACP-proof cloth covers. Where ACP are present, unprotected replants are highly likely to be infected. Replant with tolerant or resistant rootstocks or scions as they become available.
- ☐ **Barriers/Repellents:** Psyllids the edges of groves first. Create barriers such as fencing with psyllid-proof screening or windbreaks to block ACP arrival and/or apply repellents to limit ACP establishment on the perimeter of the orchard. There may be regional differences in the suitability of these tactics.
- ☐ **Visual Survey for HLB:** Conduct a visual survey for HLB symptoms in the entire orchard, including the uppermost part of tree canopies, by whatever means is possible twice a year, in late spring and late fall. Any suspicious tissue should be tested via PCR.

- [ ] **Direct CLas Detection Protocol:** Test foliage (and any psyllids found) from 100% of trees in the perimeter using direct methods of detection of the bacterium such as PCR. CDFA will test perimeter trees and psyllids in the first 400 meters of an HLB detection. Test additional trees through an approved laboratory or commercial PCR or ELISA-based kit. Report self-conducted tests with positive detections to the CDFA, which will then take regulatory action.
- [ ] **Tree Health:** Ensure appropriate nutrient and water applications to maximize root health.

Actions taken if an HLB-positive tree is found by PCR in a commercial orchard

- [ ] **Treatments at the time of an HLB detection:** When HLB is detected, the current CDFA regulations require pesticide treatment of entire orchards with broad-spectrum insecticides within a ¼ mile (400 meters) of the find site. Growers are strongly urged to extend voluntary treatments with ACP effective insecticides to 1 mile (1600 meters) from the detection site. Work with liaisons/PCD/Task forces and CDFA to determine subsequent treatments.
- [ ] **PCR positive infected tree removal:** If an infected tree or nymph (juvenile ACP) is detected by direct methods, remove the infected tree or the tree the nymph was collected from, within 1 week of test result notification, following an ACP treatment with an effective foliar neonicotinoid or pyrethroid insecticide. When removing the tree, excavate as much of the root system as possible. Plant material can be chipped in place or burned. The chippings do not present a risk of infection and can be moved safely. If stump removal is not possible, it should be ground and treated with an herbicide to prevent growth of potentially infected suckers.

ADDITIONAL CONSIDERATIONS

Isolated Orchards

Isolated orchards that are far removed from residences with HLB host plants will be easier to manage and more likely to succeed with ACP disinfestation and HLB management than orchards neighboring residences.

Organic Insecticides

The level of psyllid control needed to minimize HLB spread will be difficult to achieve with organic insecticides because of their short residual nature. In scenarios 2–3, a shift to conventional insecticides or intensified frequency of applications of organic treatments (Pyganic, Entrust, oils) are strongly recommended by University of California. The University of California recommends thatorganic treatments be applied every 2 weeks; however, if psyllid nymphs are demonstrated to remain below 0.5 nymphs/flush this duration could be extended. Conventional insecticides will be required in scenario 4 based on CDFA's mandatory 400-meter treatment in response to an HLB detection.

Early Detection Technologies (EDTs) as Emerging Tools

There are currently no EDTs broadly available that have completed the process of rigorous scientific review. However, should that process be completed in the future, using EDTs to quickly test whole orchards, or orchard perimeters, for HLB would undoubtedly be a valuable tool. EDTs currently under review include canine-based detection, protein-based detection, and altered metabolic, volatile organic compound, or microbial community profiles. Some of these EDTs will be considered "indirect" tests; in other words, the test detects some secondary change related to the infection rather than the bacteria itself. Should a tree test positive with an indirect EDT, tree removal is not currently required, but growers should take additional action.

At this time, if plant material is moved off-site to be tested with any EDT, the testing agency is required to report that information, and any positive test results, to the CDFA. Self-performed testing with an indirect EDT, which does not involve moving plant material off-site, does not currently require any reporting.

If EDTs become available to detect quiescent (hidden) infections, sample trees in the border row/tree once a year. Research suggests that testing with multiple EDT methods may improve the confidence of the results. While tree removal based on an EDT test is voluntary, take action on any tree that is a suspect positive. Remove the tree or cover it with psyllid-proof material and retest it yearly with a direct method. If an EDT indicates a tree may be infected, reporting that information to CDFA is voluntary if the tested plant material is not removed from the orchard.

A Note about Biological Control:

The biological control agent *Tamarixia radiata* is available commercially, however biological control agents do not suppress psyllid populations low enough year-round to prevent disease spread. Therefore, the grower voluntary response is based on insecticide treatments, barriers, repellents and other methods to reduce psyllids to very low levels.

SCIENTIFIC RATIONALE FOR RECOMMENDED VOLUNTARY GROWER RESPONSE TO HLB

Holly Deniston-Sheets and Beth Grafton-Cardwell

Explanation of Scenario cut-offs:
The triggers for scenario changes are based on data regarding the natural dispersion range of the ACP and/or observed spatiotemporal patterns of ACP and HLB spread.

Scenario 1: Orchards outside a 5-mile quarantine zone
Growers under this scenario should largely be practicing preventative tactics to exclude ACP from their orchards, prevent ACP establishment should incursion occur, and be on guard for the appearance of HLB or ACP. Growers should be vigilant even when finds seem far away, as HLB spread over 50 miles has been documented over the course of one year (Flores-Sánchez et al., 2017).

Scenario 2: Orchards between 1 and 5 miles from an HLB detection
These orchards are at risk for natural psyllid dispersion into the area. Research has shown that psyllids move with some regularity between trees, including between neighboring orchards within a matter of days (National Academies of Sciences, 2018; Boina et al., 2009). ACP is typically detected within about 3 miles from another ACP find (Daugherty, unpublished), and the presence of unmanaged orchards within 2.5 miles virtually guarantees psyllid invasion (Belasque Jr., et al., 2010).

Scenario 3: Orchards within 1 mile of an HLB detection, but not known to be infected
Growers within this zone should be practicing extreme caution, as ACP are capable of continual flight around ¾ mile (National Academies of Sciences, 2018), meaning that incursion of psyllids into neighboring orchards is probable, as it is not limited by their natural flight capacity.

Scenario 4: CLas detected within an orchard
The high latency period of HLB infection means that multiple HLB detections in an orchard are indicative of a much larger cryptic infection. In Brazil, for example, research has shown that more than 90% of an orchard is likely infected if only 28% of an orchard is symptomatic (Craig et al., 2018). Because the edge effect is supported by a wealth of evidence, multiple HLB infections in the interior of an orchard should be considered signs of an advanced infection (Leal, et al., 2010; Luo et al., 2014; Gottwald et al., 2008; Sétamou & Bartels, 2015; Shen et al., 2013).

The following actions have been recommended regardless of proximity to CLas:

Scouting
One adult ACP female can lay over 700 eggs in her lifetime (Liu & Tsai, 2000; Hall , 2008), and an ACP population can double in less than a month (Sule et al., 2012). Regularly scouting for psyllids will ensure that an infestation does not catch growers unaware. Scouting is generally recommended every 2–4 weeks, depending on the season and age of the tree. Young, vigorously growing trees, which are highly attractive to psyllids, could require scouting as often as once a week. Mature trees during periods of psyllid dormancy could be monitored once per month. Every 2 weeks is suggested as the normal protocol during periods of flushing, especially during the fall when psyllids are most common (Grafton-Cardwell, et al., Revised continuously; Stansly et al., 2009). Psyllid populations can continually infect orchards from outside areas, so a regular scouting program is imperative (Hall & Gottwald, 2011).

There is an abundance of evidence that psyllids colonize the borders of orchards before the interior (Sétamou & Bartels, 2015; Luo et al., 2014; Gottwald et al., 2008). To maximize the chance of psyllid detection, as well as minimize unnecessary labor costs, this is where sampling should take place. One center row should also be sampled, to determine if psyllid movement farther into the orchard has occurred. Sample a single flush from each of 10 trees along each border. Flush should be sampled to detect psyllids because psyllids require flush to feed and lay eggs (Grafton-Cardwell, et al., Revised continuously). Research has shown this is an appropriate number of samples to detect psyllids (Sétamou et al., 2008). In regions where areawide control is practiced, treatment is recommended before psyllids reach 0.5 nymphs per flush, or 2 of 10 flushes are infested (Grafton-Cardwell, personal communication).

Visual Survey

Most scientists recommend regularly identifying and removing infected trees (Hall & Gottwald, 2011). Because PCR testing of entire orchards is fiscally and logistically prohibitive, visual scouting for disease symptoms is recommended. Confirming HLB in trees is difficult, but symptoms can be used to detect leaves that are more likely to contain CLas bacteria (Louzada et al., 2016). Symptoms are irregularly distributed and CLas has been found in higher concentrations farther from the trunk, so visual surveys need to view aerial parts of the canopy (Teixeira et al., 2008).

Barriers

Although other agricultural pests may be tolerated until an economic threshold is reached, the presence of any ACP should not be tolerated, as HLB can be spread even at low insect densities (Gutierrez & Ponti, 2013; Bassanezi, et al., 2013). Although aggressive ACP control is always suggested, methods to prevent the entry of ACP into an orchard should also be considered a valuable tool.

Research has shown that 96% of adult psyllids fly at heights less than 7 ft, and >99% of ACP fly at less than 9 ft. Fencing with ACP-impermeable mesh on the perimeters of an orchard, which extends above these heights, has been shown to substantially reduce psyllid introduction into orchards (Setamou et al., 2018). Live windbreaks at borders, while potentially not as effective as fencing, have also been shown to reduce psyllid numbers in orchards (Martini et al., 2015). These 2 techniques could also be combined, with fencing being implemented as windbreaks mature.

These techniques do not need to be implemented around the entire perimeter of the orchard to be beneficial. Perimeter exclusion methods installed only on the sides of the orchard most likely to be invaded by psyllids (e.g. those closest to roads, residential areas, etc.) have been shown to successfully reduce psyllid incursion (Setamou et al., 2018).

Other methods to prevent psyllids from settling or feeding on leaves have also been investigated. Products formulated with kaolin clay have been shown to reduce psyllid numbers on flush by 60% (adults) to 78% (nymphs) (Hall et al., 2007). Individual protective tree covers have also been effective by physically excluding psyllids from trees (Graham et al., 2018). These methods should be considered especially for young trees (such as new plantings or replants), as they are more susceptible to a rapid decline following HLB infection (Gottwald, 2010) and tend to flush more frequently, which attracts the psyllids (Stansly & Rogers, 2006; Stansly et al., 2017).

Tree health

CLas colonizes roots before leaves, leading to root damage even before foliar symptoms appear (Johnson, Wu, Bright, & Graham, 2014). HLB infections lead to significant root mass loss, which could make trees more susceptible to other stressors, such as freezes and droughts (Graham, Johnson, Gottwald, & Irey, 2013). Such stressors could negatively impact yield and quality, so appropriate nutrient and water management should be practiced to potentially offset these effects (National Academies of Sciences, 2018). It should be noted, however, that not all peer-reviewed literature directly supports this recommendation. It is possible that any benefits of such treatment are not seen in short-term studies.

The following items are differentially recommended depending on the situation.

Insecticides

Aggressive ACP control with broad-spectrum insecticides is still considered the best method of limiting HLB spread (Boina & Bloomquist, 2015; Grafton-Cardwell et al. 2013; McCollum, personal communication). Extensive screening of insecticides has been conducted in Florida and California (Grafton-Cardwell, Stelinski, & Stansly, 2013; Qureshi & Stansly, 2009) and pyrethroids and neonicotinoids (thiamethoxam and imidacloprid) have proven extremely effective. They also have the added benefit of having the longest residual effect, especially the systemic formulations, (Boina & Bloomquist, 2015; Qureshi, Kostyk, & Stansly, 2014). These treatments have been shown to locally eradicate psyllids in the San Joaquin Valley for periods of up to several years. Consequently, it is recommended that their use be continued as necessary. In southern California, rotating pyrethroids as winter sprays and neonicotinoids as fall treatments should also be continued, as this sort of practice is considered more effective than any other (Boina & Bloomquist, 2015). Organic insecticides, in contrast, have little to no residual time, and therefore much more limited efficacy compared to conventional treatments (Qureshi, Kostyk, & Stansly, 2014; Technical Working Group, 2009). These treatments allow psyllids to escape and/or reinvade orchards rapidly (Boina & Bloomquist, 2015; Tofangsazi et al., 2018) and are not recommended.

Orchards with HLB finds within 400 meters are required to use broad spectrum insecticides, as part of the CDFA regulatory response. Orchards beyond 400 meters, but within 1 mile of an HLB detection, are recommended to use broad-spectrum treatments. Treatments may be applied to just the perimeter of mature orchards in scenarios 1 and 2 if sampling demonstrates that the psyllids reside exclusively on the borders. In scenarios 3 and 4, the whole orchard is treated to protect the trees from disease spread. Young orchards should always be treated in their entirety.

Although only 1 fall treatment is recommended in Coachella, Temecula, San Diego and Imperial, 2 fall treatments are recommended for Ventura, Santa Barbara, San Bernardino and central Riverside. In the latter areas, 1 fall treatment did not sufficiently suppress psyllids in 2017 (Grafton-Cardwell 2019) and task forces and PCDs in these regions have shifted to two fall treatments.

When other citrus pests require treatment, use an insecticide which is also effective against ACP whenever possible (Rogers, 2008).

PCR Testing (or other direct)

The presence of the bacteria that causes HLB can be directly confirmed by PCR, which is the current industry standard for testing (Li et al., 2006). Other direct testing methods could be utilized should they be developed.

EDTs

There are currently no EDTs broadly available that have completed the process of rigorous scientific review. However, should that process be completed in the future, using EDTs to quickly test whole orchards, or orchard perimeters, for HLB would undoubtedly be a valuable tool. EDTs currently under review include canine-based detection, protein-based detection, and altered metabolic, volatile organic compound, or microbial community profiles. Some of these EDT's will be considered "indirect" tests; in other words, the test detects some secondary change related to the infection rather than the bacteria itself. Should a tree test positive with an indirect EDT, tree removal is not currently required, but growers should take additional action.

At this time, if plant material is moved off-site to be tested with any EDT, the testing agency is required to report that information, and any positive test results, to the CDFA. Self-performed testing with an indirect EDT which does not involve moving plant material does not currently require any reporting.

Infected tree removal

Tree removal has historically been part of the management program for HLB. The intent of tree removal is to reduce the amount of inoculum available to contaminate uninfected psyllids (Craig et al., 2018; National Academies of Sciences, 2018) . A lack of on-farm management, both not rogueing trees and not controlling psyllids, increases HLB incidence for the farmer as well as for their neighbors. The presence of farms without rigorous ACP/HLB management threatens the whole citrus industry (Belasque Jr. et al., 2010). In California, where disease incidence is currently at low levels, rogueing infected trees is always recommended and should be combined with aggressive ACP control.

Mathematical models based on HLB epidemiology have shown that once detectable infections occur in 5% of trees within an orchard, it is likely that 90% of the orchard is infected (Craig et al., 2018), even in the presence of control.

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CPDPP

CITRUSINSIDER.ORG

The Citrus Pest & Disease Prevention Program is an initiative funded by California citrus growers and administered by the California Department of Food and Agriculture dedicated to combating serious pests and diseases that threaten the state's citrus trees.

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Citrus Pest & Disease Prevention Program

CITRUS **INSIDER**

(/)

CPDPP

CITRUS PEST & DISEASE PREVENTION PROGRAM

2017–2018 ANNUAL REPORT

CONTINUING TO FIGHT FOR OUR INDUSTRY'S LONGEVITY REQUIRES TEAMWORK

For more than two centuries, citrus has grown strong in California's yards and groves – serving as a source of nourishment, income and tradition for many different individuals – but all of this is at risk due to Huanglongbing's (HLB) growing presence in California.

In 2018 HLB was found in more than 600 residential citrus trees in Southern California, and despite the program's thorough surveying efforts, HLB has not been found in a commercial grove, but we must continue to hold strong. It has never been more important for all of us – including the Citrus Pest & Disease Prevention Program (CPDPP), regulatory authorities, the citrus industry, the scientific community and others – to work together to prevent the spread of the disease and save California's citrus industry.

While much has changed since the citrus industry came together ten years ago to support the creation of the CPDPP, one constant remains: the program's dedication to fight HLB. This year, the Citrus Pest & Disease Prevention Committee (CPDPC) created a strategic plan for combatting HLB now and in the future. The plan identified five prioritized strategies to achieve CPDPP's goals of keeping HLB out of commercial groves, limiting Asian citrus psyllid (ACP) movement in the state and fine-tuning the program. In addition, the program agreed to align its annual budget in support of the strategies, which can be viewed in this report.

With this plan comes additional responsibilities for all individuals involved. The CPDPC understands HLB isn't the only issue posing a threat to your business and our industry – but it's

Looking forward, much is at stake for California citrus growers, packers and workers as the industry faces its biggest threat yet in HLB. I encourage you to connect with the program, your local pest control district or task force, and follow best practices for managing the ACP and HLB. If we sit idle, hoping others will take action for our benefit, we are welcoming this devastating disease into our groves.

But, by working together, we can protect California's commercial citrus industry from devastation – sustaining our livelihood and the legacy of California citrus.

Jim Gorden, Citrus Pest & Disease Prevention Committee Chair

CALIFORNIA CITRUS

$3.3 BILLION IN PRODUCTION

21,600 JOBS

268,500 ACRES

one we can't ignore. This report highlights the many activities the program and our partners are doing across the state to protect commercial groves from HLB, but we are only as strong as our weakest link.

$7.1 BILLION ECONOMIC IMPACT

According to a report by the University of California, Riverside about 2016-2017

CONTINUED PARTNERSHIP PROVIDES BEST PATH TO PROTECTING CALIFORNIA CITRUS

Citrus trees are a critical piece of the state's agricultural landscape – from backyard trees beloved by homeowners to the rolling acres of beautiful and fragrant commercial citrus trees – and the California Department of Food and Agriculture (CDFA) is committed to working with the citrus industry to fight Huanglongbing (HLB).

The department is continuing to explore and employ new methods that keep the program on track to attain its goals: preventing HLB's spread to commercial groves, limiting Asian citrus psyllid (ACP) movement around the state and continuing to fine tune the program.

In the past year, CDFA has used the best available science to create a more efficient laboratory and thorough HLB sampling program. CDFA's lab has implemented the use of a new primer when testing plant samples for the bacteria that improves our ability to detect HLB quickly. This primer is much more selective and sensitive to the presence of the bacteria that causes HLB, and it has provided us with more concrete positive and negative results – reducing the amount of inconclusive results by 60 percent.

In the field, agriculture crews are now conducting quadrant sampling of host trees that are on the same property or on adjacent properties to those with confirmed HLB detections. Field crews divide the tree into four sections and take a sample from each of those four sections to be separately tested. This helps us find HLB more quickly than taking one sample from each tree, and this sampling change has directly contributed to the department's identification and removal of more than 600 HLB-positive citrus trees in 2018.

While we have made strides toward a more efficient program, there is still more to be done. Looking forward, the department will continue to partner with the citrus industry and the scientific community to fight HLB on all fronts.

Victoria Hornbaker, Interim Citrus Program Director, California Department of Food and Agriculture

BY THE NUMBERS

During FY 17-18, the Citrus Pest & Disease Prevention Program used its funds to support its strategic priorities and fight HLB on multiple fronts.

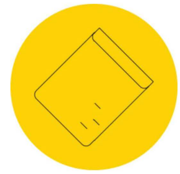
ON THE GROUND

676	residential citrus trees confirmed HLB+ and removed
129,118	residential properties surveyed for Asian citrus psyllid
49,229	residential properties treated for Asian citrus psyllid
3,800,000	tamarixia radiata released

IN THE LAB

89,155

citrus plant samples tested for HLB



67,753

ACP samples tested for Candidatus Liberibacter asiaticus

EXPENDITURES

Strategic Priority 1 Quickly Detect and Eradicate Diseased Trees: **$13,182,757**	Strategic Priority 2 Control Movement of Psyllid Around the State; Enforce Regulations: **$3,450,200**	Strategic Priority 3 Suppress Asian Citrus Psyllid Populations: **$12,215,904**
Strategic Priority 4 Improve Data Technology, Analysis and Sharing: **$235,180**	Strategic Priority 5 Outreach and Collaboration: **$1,702,526**	Administrative **$1,922,775**

REVENUES

TOTAL FUNDS: $39,440,000

Assessment on cartons of citrus: **$15,000,000**

US Dept. of Agriculture, Citrus Health Response Program: **$14,440,000**

California's General Fund: **$10,000,000**

A DEEPER LOOK AT THE PROGRAM

THE CITRUS PEST & DISEASE PREVENTION PROGRAM'S SUBCOMMITTEES KEEP THE PROGRAM

This subcommittee continues to look at new ways – that are backed by science – to improve the program's operations and

SCIENCE AND TECHNOLOGY

IN ALIGNMENT WITH ITS STRATEGIC PLAN AND HELP THE PROGRAM MOVE MORE NIMBLY AS ISSUES ARISE. THE FOLLOWING HIGHLIGHTS THE ACTIVITIES THAT POSITIVELY IMPACTED THE PROGRAM, CITRUS TREE OWNERS AND CALIFORNIA'S CITRUS INDUSTRY.

FINANCE

Bob Felts Jr., subcommittee chair and owner of Felts Farm in Visalia

As the subcommittee that oversees the program's multi-million-dollar annual budget, the finance subcommittee developed a balanced budget for FY 18–19 that closely adheres to the priorities outlined in the program's strategic plan. Additionally, the subcommittee has worked closely with CDFA on exploring ways to secure dedicated program resources designated solely to help protect California's citrus industry from HLB. More details on budgets and expenditures overseen by the finance subcommittee can be found below.

OPERATIONS

Keith Watkins, subcommittee chair and vice president of Bee Sweet Citrus

To maximize resources and efficiencies, the operations subcommittee – comprised of citrus growers and packers – changed the protocol of CDFA's field crews to focus on sampling plant material for HLB in areas that have been infested with the Asian citrus psyllid for many years, rather than trapping for the psyllid in those already infested areas. ensure resources are used wisely. Additionally, the operations subcommittee spearheaded efforts, alongside grower liaisons and California Citrus Mutual, to identify neglected or abandoned groves and develop a course of action with county governments to get those groves treated or removed.

OUTREACH

Mark McBroom, subcommittee chair and owner of Bloom to Box Crop Care in Imperial County

The outreach subcommittee continued to evolve its strategy to inform California homeowners, local governments and elected officials, and members of the citrus industry – from the picker to the hauler and everyone in between – about best practices to prevent the spread of HLB. Media coverage, advertising and informational materials about the pest and disease garnered an estimated 110 million impressions from California residents.

Partnerships with California Citrus Mutual, Citrus Research Board, California Association of Pest Control Advisers, the University of California, County Agricultural Commissioners and other groups critical in the fight of HLB helped the program reach different players in the citrus industry. Moving forward, the outreach team is committed to continuously evaluating its strategy and moving quickly to address issues as they arise.

Etienne Rabe, subcommittee chair and vice president of horticulture for Wonderful Citrus

The science and technology subcommittee continued to use the best available science to make program recommendations that help prevent the spread of HLB to commercial groves and limit psyllid movement. For example, as a result of research from Dr. Beth Grafton-Cardwell of the University of California, the subcommittee established the two optimum treatment times and types for residential citrus trees in the buffer around commercial citrus groves participating in the coordinated treatments and treatments along the U.S.-Mexico border. Additionally, the group is working with researchers to explore alternate mitigation methods, including new post-harvest treatment options for the movement of bulk citrus. As the program advances, the science and technology subcommittee will continue to consult the best and brightest researchers and scientists to help the program make solid science-based decisions.

All committee and subcommittee meetings are open to the public and can be attended in person, via phone or webinar. Visit cdfa.ca.gov/citruscommittee (http://cdfa.ca.gov/citruscommittee) for a calendar of upcoming meetings.

2019-2020 ANNUAL **REPORT**

OUR BIGGEST BATTLE: MAINTAINING URGENCY AMID SUCCESS

For more than a decade, the California citrus industry has invested countless hours, leveraged millions of dollars and created dozens of innovative partnerships in an effort to keep Huanglongbing (HLB) out of our commercial groves – and it has worked.

I recognize that this feeling of accomplishment is encouraging. However, with success, the urgency and magnitude of this threat can feel diminished, and nothing could be further from the truth. The devastating impact that HLB can have on our orchards, communities and livelihoods is still very real, even if – for now – we're successful at remaining one step ahead.

As we look back on the last year, this report will focus on the many activities the program and its partners have conducted to protect commercial citrus groves. However, I can't stress too strongly the need for all growers' cooperation in making these efforts successful. We need you to get involved! We cannot do it alone. Connect with your local grower liaison, pest control district or task force. Do everything you reasonably can to prevent Asian citrus psyllid (ACP) and HLB from becoming established or getting too comfortable in your orchard. The cost to manage the ACP is far less than any potential costs or loss to the industry that HLB could pose.

This past year has presented many unforeseen challenges to our industry – and the entire world.

Through all the obstacles presented by the COVID-19 pandemic, the Citrus Pest & Disease Prevention Committee has continued working to support the needs of the industry by identifying opportunities for increased efficiencies, exploring emerging mitigation methods and using innovative tactics to connect with audiences in an increasingly digital world.

While we cannot predict what the future will hold, we can plan for scenarios that may become reality and continue to put in the tough, but necessary, work to best protect California's commercial citrus industry. Together we can keep California's citrus healthy.

Jim Gorden, Citrus Pest & Disease Prevention Committee Chair

269,700
acres of
commercial citrus
in California

USDA's National Agricultural Statistics Service (NASS) acreage survey (2019-2020)

California
accounted for 52% of the nation's
citrus production and 63% of the
total citrus value in the U.S.

California Agricultural Statistics Review, 2019-2020, California Department of Food and Agriculture

STRENGTHENING THE FIGHT TO SAVE CALIFORNIA'S CITRUS WITH A DEDICATED WORKFORCE

As we began the 2019-2020 fiscal year, we anticipated a year of growth. The newly created Citrus Pest and Disease Prevention Division (CPDPD) at the California Department of Food and Agriculture (CDFA) continued to scale up as a dedicated statewide workforce was established to support the citrus industry's fight against invasive pests and diseases. Little did we know how much this year would challenge all of us to nimbly adjust and grow to meet the unique circumstances we've faced as an industry and a society.

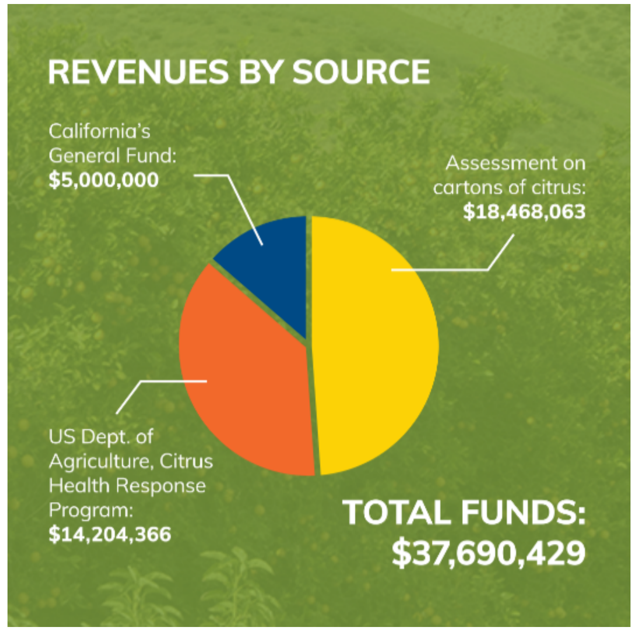
Collaboration has always been a guiding principle in the fight again the Asian citrus psyllid (ACP), Huanglongbing (HLB) and other citrus pests and diseases. Citrus industry members, United States Department of Agriculture (USDA), CPDPD, county

While we have made great strides in overcoming the year's challenges, we are more committed than ever in our partnership to you – the citrus industry – and in our continual pursuit of the most innovative and efficient ways to fight ACP and HLB.

Victoria Hornbaker, Director,
Citrus Pest and Disease Prevention Division
California Department of Food and Agriculture

agricultural officials, scientists and researchers have worked together to innovate, adapt and implement protocols to stay a step ahead of these threats. This commitment to partnership was reinforced when the CPDPD – funded by California citrus growers and USDA and administered by CDFA – was established by the state. The CPDPD has worked diligently to fill the 168 dedicated positions allocated to serve the California citrus industry, this includes management, field staff and analytical scientists located across 11 field offices strategically placed throughout California and all committed to a rapid and unrelenting response to ACP and HLB.

Like many organizations in 2020, CPDPD staff and activities were forced to continuously adjust to ensure our work remained safe, yet effective. The CPDPD adapted its surveying and treatment techniques to protect public and staff health, as well as turned to virtual formats to communicate with stakeholders. In fact, moving to online platforms for industry and public meetings has not only reduced costs, but also increased participation. With support from the committee and the scientific community, the division also instituted several changes to increase the efficiencies, including streamlining bulk citrus movement regulations, and reducing HLB and areawide ACP treatment areas to 250-meter area to limit cost and increase completion times.



BY THE NUMBERS

During FY 19-20, the Citrus Pest & Disease Prevention Program used its funds to support its priorities and fight HLB on multiple fronts.

ON THE GROUND

453
Residential citrus trees confirmed HLB+ and removed

90,826
Residential properties surveyed for the Asian citrus psyllid

65,742
Asian citrus psyllid sticky traps deployed throughout the state

IN THE LAB

68,910
citrus plant samples tested for HLB in authorized labs

36,248
Asian citrus psyllid samples tested for CLas

EXPENDITURES BY CATEGORY*

$9,522,179
Quickly Detect and Eradicate Diseased Trees

$2,839,818
Control Movement of Psyllid Around the State; Enforce Regulations

$7,530,353
Suppress Asian Citrus Psyllid Populations

$595,794
Improve Data Technology, Analysis and Sharing

$1,987,290
Outreach and Collaboration

$2,539,758
Administrative

**Expenditures reported as of March 2021*

FACTS AND FIGURES

3,721,661
Tamarixia radiata released in 13 regions throughout California and surrounding areas

11
field offices across the state

168
division staff members dedicated to supporting the citrus industry

53
public meetings were held in person or virtually by CPDPD

KEEPING THE COMMITTEE ALIGNED TOWARD POSITIVE CHANGE

The subcommittees of the Citrus Pest & Disease Prevention Committee work to ensure committee activities are in alignment with its strategic priorities and help the program navigate

OUTREACH

Mark McBroom, subcommittee chair and owner of Bloom to Box Crop Care in Imperial County through new challenges and issues, including the COVID-19 pandemic. The following highlights the activities that positively impacted the program and California's citrus industry this past fiscal year.

FINANCE

Bob Felts Jr., subcommittee chair and owner of Felts Farm in Visalia

As it strives to increase the efficiency, clarity and transparency of the program's revenues and expenditures, the finance subcommittee consistently communicates with Citrus Pest and Disease Prevention Division staff to ensure the committee has a firm understanding of program successes and areas for improvement. This year, the subcommittee used a new manual tracking system instituted within the division to more accurately determine where program resources stand in a timely manner and continues to explore methods for streamlining the invoicing process. In developing the FY 2020-2021 budget, the finance subcommittee worked closely with the operations subcommittee to anticipate and plan for future expenditures. More details on budgets and expenditures overseen by the finance subcommittee can be found in this report.

OPERATIONS

Keith Watkins, subcommittee chair and vice president of Bee Sweet Citrus

With a laser focus on efficiency without compromising efficacy, the operations subcommittee works closely with the science and technology subcommittee, the University of California and the Citrus Research Board's, Data Analysis Tactical Operations Center (DATOC) to ensure any operational changes are rooted in sound science and supported by data. Based on scientific insights, the subcommittee recommended reducing Huanglongbing (HLB) treatment areas to 250 meters as this area would encompass 95 percent of HLB detections, increase completion times and save resources. Additionally, the group recommended maintaining bi-monthly trap servicing in the Central Valley to prevent undetected Asian citrus psyllid (ACP) population growth and identified opportunities to streamline the bulk citrus movement regulations to avoid potential work arounds. Backed by science, the subcommittee continues to explore how to manage ACP and HLB in the most efficient way.

To ensure the program's messaging continues to drive desired behaviors among homeowner audiences, the outreach subcommittee began the year by conducting market research with homeowners to evaluate motivators and willingness to act and refine key messages to support these findings. The abrupt shifts of the COVID-19 pandemic caused many traditional activities to move to the digital sphere when connecting with homeowners, industry members and elected officials. Digital connections quickly became a primary conduit to maintaining urgency among stakeholders and the subcommittee pivoted to adapt to virtual city council presentations, online grower meetings, video field crew trainings, Zoom media interviews and social media marketing to continue to meet the program's outreach needs. Overall, the program's outreach efforts reached millions of Californians through several touch points, including social media advertisements, community events, direct mailers and over 250+ earned media stories in several print, broadcast and radio outlets. The subcommittee continues to explore new ways to collaborate with partners and leverage new communication channels to adapt to stakeholders' changing routines and news consumption habits.

SCIENCE AND TECHNOLOGY

Etienne Rabe, subcommittee chair and vice president of horticulture for Wonderful Citrus

The science and technology subcommittee uses the best available science to make program recommendations that help prevent the spread of HLB into commercial groves, limit psyllid movement and increase program efficiency. In close association with DATOC and the operations subcommittee, the science and technology subcommittee actively explore ways to ensure optimal use of program resources. For example, HLB mitigation boundaries and area-wide buffer treatment areas were reduced from 400-meters to 250-meters to increase timeliness of treatments and reduce costs. Additionally, in its continuous evaluation of program effectiveness against HLB, the group is exploring alternate scientifically sound mitigation methods that will produce cost savings while protecting the health of commercial citrus to ensure we have a prosperous and healthy citrus crop for years to come.