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A social-ecological systems perspective of huanglongbing management in California

By

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DISSERTATION

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ABSTRACT

Huanglongbing (HLB) is an invasive disease of citrus trees associated with the bacterium "*Candidatus* Liberibacter asiaticus" and transmitted by the Asian citrus psyllid (ACP), *Diaphorina citri*, that is threatening citrus production in California and other citrus-producing areas of the world. Current strategies to prevent citrus trees from being infected with HLB are based on the application of coordinated insecticide treatments for the insect vector, detection and removal of HLB-positive trees and use of certified plant material. These measures are most effective if applied on an area-wide scale by all citrus growers in a region, yet little is known about California citrus growers' willingness to coordinate measures across property boundaries. When individuals need to make contributions to achieve a collective effort but may benefit from the efforts of others without bearing the costs, they may be tempted to free-ride on others' efforts, giving rise to a collective action problem. This type of problem has been extensively studied by the social-ecological systems literature, but it has rarely been addressed in the context of plant diseases.

In this dissertation, a social-ecological systems perspective was used to integrate the social and ecological dimensions of HLB management in order to explore what strategies may be more effective to achieve collective action for this disease. The first chapter introduces the idea of plant health provision as a public good collective action problem. Ostrom's design principles for long-enduring common-pool resource institutions are used as a reference to compare the institutional approaches that have been developed to achieve collective action for HLB in California and other citrus-producing areas, illustrating how these principles could be applied to other plant diseases that are threatening food security, and suggesting a link between institutional approaches that follow the design principles and successful collective outcomes. The second chapter explores the

California citrus industry's propensity to adopt voluntary measures to manage HLB. A multivariate ordinal logistic regression model is used to analyze a survey distributed to 300 participants, showing that the propensity to adopt management measures may depend on the citrus stakeholder's perceived vulnerability to HLB, as well as their intention to stay informed and communicate with the regional coordinators of the HLB control program and their neighbors. In addition, the analysis sheds light into what combinations of management measures may be adopted together as an integrated pest management approach to HLB. The third chapter focuses on the area-wide management (AWM) program for ACP in Southern California, examining the individual perceptions and group-level determinants of collective action for AWM. It shows that citrus stakeholders are aware of the benefits of coordinating insecticide treatments for ACP, but they identify the lack of participation as the main obstacle for collective action, and some do not believe that their neighbors will coordinate. To face this collective action problem, two distinct institutional approaches have been developed to coordinate insecticide treatments for ACP, one in which treatments are voluntary, and one in which they are mandatory. An analysis of participation in AWM in Southern California over nine seasons shows that these two institutional approaches have followed a different trajectory over time. In addition, group-level variables from collective action theory, such as the size of the group or the heterogeneity in grove size, have had a negative impact on participation and may be relevant for the design of future AWM programs.

This dissertation contributes to answering the question of what institutional approaches and strategies might be more effective to deal with the spatial and temporal dynamics of plant diseases while staying aligned with the preferences, values and needs of the societies affected, setting the basis for further interdisciplinary research that will likely benefit the management of HLB and other plant diseases that give rise to collective action problems.

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Chapter 1:

Institutional approaches for plant health provision as a collective action problem

ABSTRACT

The provision of plant health has public good attributes when nobody can be excluded from enjoying its benefits and individual benefits do not reduce the ability of others to also benefit. These attributes increase risk of free-riding on plant health services provided by others, giving rise to a collective action problem when trying to ensure plant health in a region threatened by an emerging plant disease. This problem has traditionally been addressed by government intervention, but *top-down* approaches to plant health are often insufficient and are increasingly combined with *bottom-up* approaches that promote self-organization by affected individuals. The challenge is how to design plant health institutions that effectively deal with the spatial and temporal dynamics of plant diseases, while staying aligned with the preferences, values and needs of affected societies. Here, we illustrate how Ostrom's design principles for collective action can be used to guide the incorporation of *bottom-up* approaches to plant health governance in order to improve institutional fit. Using the ongoing epidemic of huanglongbing (HLB) as a case study, we examine existing institutions designed to ensure citrus health under HLB in Brazil, Mexico, the United States and Argentina, and discuss potential implications of Ostrom's design principles for the collective provision of plant health under HLB and other plant diseases that are threatening food security worldwide. The discussion leads to an outline for the interdisciplinary research agenda that would be needed to establish the link between institutional approaches and plant health outcomes in the context of global food security.

INTRODUCTION

Plant health, the well-being of individual plants and communities in cultivated and natural ecosystems, is increasingly being threatened by plant pests and diseases (Giovani et al. 2020; MacLeod et al. 2010), fostered by climate change and the integration of the global economy (Bebber et al. 2014; Liebhold et al. 2012). Viral diseases vectored by insects such as the whitefly *Bemisia tabaci* or the Western flower thrips *Frankliniella occidentalis* (Gilbertson et al. 2015), fungal diseases such as 'Panama disease', caused by *Fusarium oxysporum* f. sp. *cubense* tropical race 4 (Maymon et al. 2020), or bacterial diseases such as Olive Quick Decline Syndrome, caused by *Xylella fastidiosa* sp. *pauca* (Schneider et al. 2020), are current examples of invasive plant diseases that have been detected outside their native habitat and have triggered costly emergency responses. When introduced into a new territory, invasive plant diseases can pose a significant risk to crop production and ecosystem services (Boyd et al. 2013; Paini et al. 2016; Simberloff et al. 2013), and they can be a major threat to food security, as they can limit the availability, quality and/or economic access to food (Fones et al. 2020; Savary et al. 2017). Because of these threats, many studies have been devoted to understanding the spread of plant diseases and developing management strategies, but fewer studies have examined how people coordinate efforts when implementing those strategies (McAllister et al. 2015).

When people face the challenge of protecting plant health from a disease spreading across a region, a *collective action problem* may arise. This occurs when individuals must choose whether to make a costly effort towards achieving some group-level goal, but because they can individually benefit from the efforts of others without bearing the costs, they have an incentive to reduce their effort or withdraw it completely; *i.e.* to free ride. If enough individuals free ride, the group goal may not be achieved (Gavrilets 2015). Collective action problems are inherent to situations in which individuals cannot be excluded from the benefits of others' efforts, such as in the provision of public goods (Sandler 2015).

Preserving plant health from disease has public good attributes because one grower's benefits from low disease pressure does not reduce the ability of others in the affected region to also benefit (*i.e.,* it is *non-rivalrous*), and no grower can be excluded from the benefits of healthy production (*i.e.,* it is *non-excludable)* (Lansink 2011). Pioneering studies proposed that invasive species management generated environments free of invasive species that also had public good attributes (Perrings et al. 2002; Sumner 2008), and the concept of reducing invasive species or weeds as a public good has been reviewed recently (Bagavathiannan et al. 2019; Graham et al. 2019, Niemiec et al. 2020). In essence, the notion is that individuals pursuing their own interests by taking actions to ensure plant health on their own properties can benefit from provision generated by nearby properties. Thus, they may be tempted to free ride on others' efforts. This sets up the classic collective action problem outlined above. In the extreme case where a single individual can bring collective benefits to zero by, for example, not taking measures to ensure plant health on their own property and thereby keeping open an avenue for disease spread that defeats the efforts of neighbors, then plant health can be considered a weakest-link public good, in which the level of overall provision would be determined by the least effective provider (Hennessy 2008; Perrings 2016). A few recent studies have advanced this conceptualization of provision of plant health as a public good, extending the scope of the collective action problem from the management of *invasive* pests and diseases to *established* plant diseases with great spread potential (Damtew et al. 2020; Sherman et al. 2019). The crucial question that remains is: how can individuals organize effectively to achieve desired levels of protection against disease?

Institutions are the formal and informal rules, norms and conventions that societies use to structure interactions and increase predictability in situations of interdependent choice (Ostrom 2005). In *top-down* institutional approaches to plant health, governments assume regulatory command of plant health services, establishing rules to prevent disease spread and funding monitoring and management efforts (FAO 1999). Government intervention is typically justified by *under-provision* of plant health by the sum of individuals' efforts and the need to ensure food security (Epanchin-Niell 2017; Waage and Mumford 2008). However, because of high transaction costs of monitoring disease spread and enforcing management efforts across all actors, *top-down* approaches are often insufficient on their own to prevent the spread of emerging plant diseases (Colella et al. 2018; Gottwald et al. 2001). The alternatives are *bottom-up* approaches based on self-organization by the affected communities, or hybrid approaches that combine the expertise and resources of government agencies with community-based initiatives and local knowledge (Epanchin-Niell et al. 2010; John 2006). Although these alternative approaches are increasingly being exploited (Higgins et al. 2016; Mato-Amboage et al. 2019), there is a lack of institutional guidelines to effectively incorporate them into plant health governance.

We would like to offer further insight to this emerging field by examining the extent to which Ostrom's design principles for the sustainable management of common-pool resources (Ostrom 1990) can be used as a guiding framework to incorporate *bottom-up* approaches into plant health governance. Plant health institutions must deal with the inherent spatial and temporal variability of emerging pests and diseases. At the same time, they must also be aligned with the preferences, values and needs of the societies affected so that plant production can be sustained. Our goal is to show how Ostrom's (1990) principles can be used to meet these challenges and place the task of institutional design within a broader social-ecological systems framework. To ground our work in a well-documented example, we focus on huanglongbing (HLB) disease of citrus, since it exhibits many of the characteristics of invasive diseases that give rise to a collective action problem, while being widely documented and of sufficient global importance to merit attention in its own right. Using the ongoing HLB epidemic in North and South America as a case study, we explain the collective action problem associated with citrus health under HLB, document the extent to which the institutions designed to manage HLB follow Ostrom's principles, and discuss further implications of collective action theory for plant health in the context of global food security, showing how this approach could be applied to other diseases that threaten food security worldwide.

Plant health provision requires collective action

Although the collective action problem associated with plant health has been mostly characterized for invasive species (Graham et al. 2019), certain attributes of endemic plant diseases such as aerial spore dispersal (Damtew et al. 2020; Sherman et al. 2019), insect vector dispersal (Anco et al. 2019) and/or importance of primary and secondary inoculum for disease epidemics (Bergamin Filho et al. 2016) call for regional management approaches that may also give rise to collective action problems. Some of these endemic diseases, such as rice tungro disease (Cabunagan et al. 2001) or cassava brown streak disease (Legg et al. 2017), are a major threat to food security in Southeast Asia and East Africa. Despite the fact that a collective action problem was identified as the most important obstacle to integrated pest management (IPM) adoption in developing countries (Parsa et al. 2014), institutional approaches to promote plant health in these contexts have been rarely characterized (Lansing 1991). To the extent possible, we will draw parallels between HLB as the focus of our study and endemic diseases in staple crops that also require collective action.

HLB is considered the most severe threat to citrus health worldwide (Bové 2006). Most commercial citrus cultivars are susceptible to HLB (Ramadugu et al. 2016), and infected trees have reduced yield and fruit quality (Bassanezi et al. 2011; Dala-Paula et al. 2019). Once a tree is infected, there is no cure, and it will typically die (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 and by an insect vector, the Asian citrus psyllid (ACP), *Diaphorina citri* (Bové 2006). Both bacterium and vector have spread from Asia to the American continents and threaten citrus production in Brazil, Mexico, the United States and Argentina, which are among the top citrus producers worldwide (Figure 1.1).

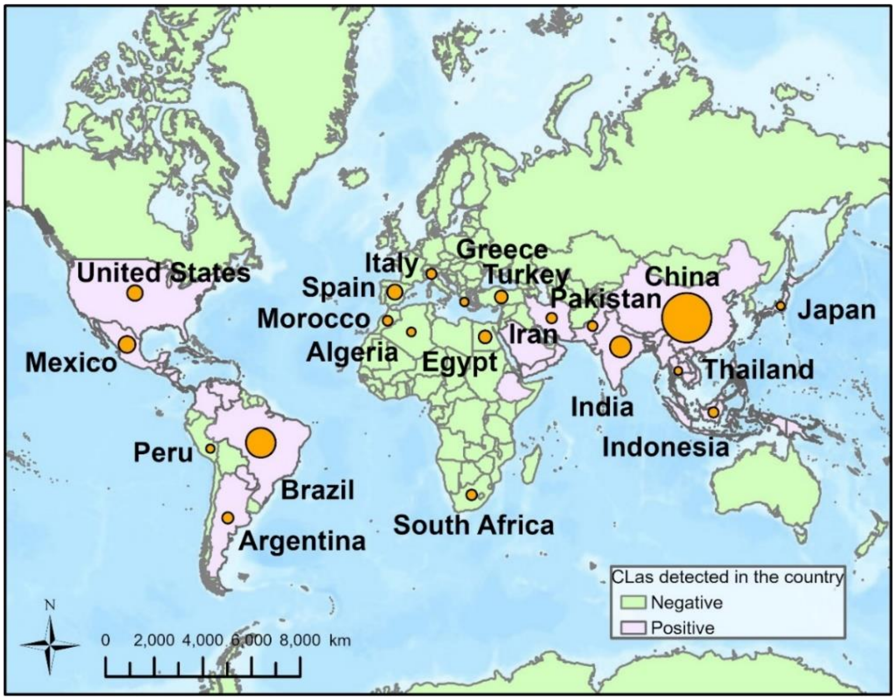

Figure 1.1: Current distribution of "*Candidatus* Liberibacter asiaticus" (*C*Las) in citrus-producing countries. Countries that have detected *C*Las are shown in pink, and countries that have not detected *C*Las are shown in green (CABI 2020a). The orange circles are proportional to the total citrus production (tonnes) of the 20 countries with the highest citrus production worldwide (FAO 2018), which have been labelled. Eleven of them (Argentina, Brazil, China, India, Indonesia, Iran, Japan, Mexico, Pakistan, Thailand, United States) have detected CLas; and nine of them (Algeria, Egypt, Greece, Italy, Morocco, Peru, South Africa, Spain, Turkey) have not detected *C*Las.

HLB is difficult to eradicate because ACP is mobile and prolific, CLas multiplies in both the insect vector and the tree, and trees are infectious long before detection is possible (da Graça et al. 2016). Vector control is key to disease management because HLB epidemics are driven by ACP that migrate into citrus groves (Gasparoto et al. 2018). Effective vector control requires *area-wide management* (AWM), which consists of time-coordinated insecticide sprays by all growers in a region (Vreysen et al. 2007). Because coordinated treatments benefit the whole group, any grower may be tempted to rely on others' treatments and avoid the cost of spraying, but if a grower fails to coordinate, that property can sustain ACP and spread HLB to the rest (Bassanezi et al. 2013). Thus, like other plant diseases (Damtew et al. 2020; Sherman et al. 2019), the challenge for HLB is how to overcome a collective action problem to ensure citrus health provision (Singerman and Rogers 2020).

A similar collective action problem arises in the area-wide management of rice tungro disease (RTD), the most important viral disease of rice in South and Southeast Asia. Tungro-infected plants show yellow to orange leaf discoloration and stunted growth, and severe infections may lead to considerable yield losses (Azzam and Chancellor 2002). RTD is caused by two viruses, *Rice tungro spherical virus* (RTSV) and *Rice tungro bacilliform virus* (RTBV), which are transmitted in a semipersistent manner by six leafhopper vector species, the most important being the green leafhopper, *Nephotettix virescens* (Azzam and Chancellor 2002). Rice plants can become infectious within one week of being inoculated, and the vector can acquire and transmit the viruses within minutes, so insecticide treatments are generally ineffective to prevent RTD epidemics, and the main management practices are the use of resistant rice varieties and area-wide synchronous planting (Savary et al. 2012). Synchronizing the timing of rice planting over a sufficiently large area imposes a non-rice period between harvest and planting when the leafhopper may lose the viruses, it may not able to feed, and transmission from fields planted earlier in the season to newly planted fields may be prevented (Savary et al. 2012). The adoption of synchronous planting in Southeast Asia in the 1970s and 1980s was successful at controlling RTD epidemics in parts of Indonesia and Malaysia, but in other areas it faced significant socio-economic and socio-cultural constraints (Azzam and Chancellor 2002). Synchronous planting increased hire rates of tractors and labor, it required an efficient irrigation network, and most importantly, it required extensive cooperation among farmers and coordination among government agencies (Cabunagan et al. 2001). Therefore, rice growers trying to synchronize their planting period to prevent RTD epidemics and ensure rice health faced a similar collective action problem to citrus growers trying to coordinate their insecticide treatments against the ACP to ensure citrus health, and parallels between institutional arrangements for RTD and HLB will be illustrated below, data availability permitting.

Likewise, cassava growers in Central and East Africa also face a collective action problem to protect their crops from cassava brown streak disease (CBSD), which is considered the greatest threat to cassava productivity in Africa (Legg et al. 2014). CBSD causes leaf chlorosis, brown streaks on the stem and root necrosis, which has devastating consequences, as cassava roots are a prime food security crop (Mbewe et al. 2020). CBSD is caused by two related viruses, *Cassava brown streak virus* (CBSV) and *Ugandan cassava brown streak virus* (UCBSV), which are transmitted in a semipersistent manner over short distances by the whitefly *B. tabaci* (Maruthi et al. 2017). Because cassava is vegetatively propagated, CBSD can also spread over long distances through trade of infected cassava cuttings. As a consequence, cassava health provision strategies are currently focused on providing certified plant material, improving CBSD surveillance and diagnosis, and breeding or genetically engineering resistant cultivars (Legg et al. 2014). To date, the area-wide use of certified cassava cuttings is one of the most viable options to ensure cassava health, but it requires compliance by most cassava growers in a region to avoid the introduction of inoculum that could be subsequently spread to nearby fields by the prevalent whitefly populations (Ferris et al. 2020). A pilot "community phytosanitation" program for CBSD that involved area-wide removal of infected plants and replanting with certified cassava cuttings was recently implemented in Tanzania (Legg et al. 2017), offering another example of how to address a collective action problem in plant health provision.

Institutional arrangements for plant health provision

In order to ensure citrus health, similar institutional arrangements to promote AWM of ACP have emerged in HLB-affected citrus regions in North and South America (Figure 1.2), following international guidelines (COSAVE 2017; FAO 2013; NAPPO 2015). Each region has implemented an emergency response to the invasive disease that contains elements of a *top-down* approach, with the National Plant Protection Organization (NPPO) leading monitoring and diagnostic efforts, nursery certification and overseeing other activities. However, each region also relies on the citrus industry and local authorities to coordinate actions, suggesting elements of a *bottom-up* approach. Although the international guidelines stress that successful AWM requires participation by all growers in a region, they do not explicitly characterize it as a collective action problem or provide institutional recommendations to prevent free-riding. Research into these aspects has been scant (NASEM 2018).

Figure 1.2: Status of the HLB epidemic in Brazil, Mexico, the United States and Argentina. Countries that have detected CLas are shown in pink, and countries that have not detected CLas are shown in green (CABI 2020a). In Brazil, Mexico, the United States and Argentina, state/province labels include the year of the first HLB-positive tree detection. For Mexico, only the 9 main citrus-producing states have been labeled. The status of the HLB epidemic per state/province was determined according to the categories used by CABI (2020b) with information retrieved from each country (Bassanezi *et al.* 2020; SENASA 2020; SENASICA, pers. comm.; USDA-APHIS-PPQ 2019). Few occurrences (yellow) indicates that HLB has been reported occasionally and its presence is rare or sporadic, which corresponds to less than 100 HLB-positive trees in Argentina and the US; and less than 10% of citrus acreage infected in Mexico. Localized (orange) indicates that HLB is present but does not occur in some suitable parts of the state. Widespread (red) indicates that HLB has been detected practically throughout the state where conditions are suitable.

Like citrus health provision, sustainable management of common-pool resources (CPRs), such as forests and fisheries, requires collective action (Ostrom 1990). CPRs are similar to public goods in that they are *non-excludable*, because they are sufficiently large to make it costly to exclude potential users from obtaining benefits from their use. However, unlike public goods, CPRs are *rivalrous*, because consumption of the resource by a user reduces availability for the rest. Both give rise to a collective action problem, which may lead to *over-exploitation* in the case of CPRs and *under-provision* in the case of public goods (Ostrom 1990).

Observations of community management of CPRs led Ostrom to identify eight institutional design principles (DPs) associated with effective self-organization (Table 1.1), which have been validated by many studies (Baggio et al. 2016; Cox et al. 2010). Because Ostrom's DPs identify conditions that build trust and reciprocity to foster and sustain collective action, our hypothesis is that the extent to which the DPs are incorporated in the regional institutional arrangements for plant health will provide insight into the likely effectiveness of collective efforts to achieve desired outcomes. The detailed example we discuss concerns HLB, but the extension of the concepts to other plant health threats is straightforward.

Table 1.1: An explanation of Ostrom's design principles illustrated by long-enduring common-pool resource institutions, based on Ostrom (1990) and Cox *et al.* (2010).

Design principle	*Explanation*
1. Clearly defined boundaries	This principle refers to the presence of well-defined boundaries around a community of users and around a resource system. The boundaries define who is responsible for collective action and over what area, which reduces the costs of monitoring behavior.
2A. Congruence between rules and local conditions	The second principle can be subdivided into two: that both appropriation and provision rules conform to local conditions (DP2A); and that there is congruence between appropriation and provision rules (DP2B). DP2A means

2B. Congruence between appropriation and provision rules	that the rules that are established for the management and maintenance of a resource are aligned with the predominant social norms, culture, and agro-ecological conditions in a community. DP2B refers to a correspondence between the rules governing contributions to the maintenance of the resource system, and the rules governing withdrawal of resources from the system.
3. Collective-choice arrangements	It was stated as "most individuals affected by the operational rules can participate in modifying the operational rules". If local users who directly interact with one another can define the rules that regulate the day-to-day decisions about the use of a shared resource, they will be in a better position to incorporate local knowledge.
4A. Monitoring users *4B. Monitoring the resource*	This principle is based on the idea that a community needs to be able to identify users that do not comply with rules; otherwise there can be no credible commitment. Monitoring should be undertaken by the resource users, not by external authorities. Monitoring the resource condition assesses the extent to which collective action is effectively providing public goods or preventing overexploitation of common-pool resources.
5. Graduated sanctions	Although sanctioning prevents an excessive violation of community rules, sanctions should be graduated based on the severity and/or repetition of violations to ensure proportionality. And they should be imposed by the resource users or officials accountable to them, to maintain community cohesion.
6. Conflict-resolution mechanisms	It was stated as "appropriators and their officials have rapid access to low-cost arenas to resolve conflicts among appropriators or between appropriators and officials". Low-cost conflict resolution prevents the cost of conflict from outweighing the benefits of successful collective action.
7. Minimal recognition of rights to organize	It was stated as "the rights of appropriators to devise their own institutions should not be challenged by external governmental authorities". Local institutions are more effective when higher levels of government allow users to self-organize in ways that reflect local social and ecological contexts.
8. Nested enterprises	It was stated as "governance activities are organized in multiple layers of nested enterprises", and it refers to the importance of connecting smaller social systems that manage different parts of a larger resource system to facilitate cross-scale coordination.

We obtained information from a variety of sources about the institutional arrangements for citrus health under HLB in Brazil, Mexico, Argentina, Florida, Texas and California, which are examined below in light of the DPs (Table 1.2).

Table 1.2: Presence of Ostrom's "Design principles illustrated by long-enduring CPR institutions" in the institutional arrangements for citrus health under HLB in different citrus-growing areas.

Design principle	*São Paulo (Brazil)*	*Mexico*	*Entre Rios (Argentina)*	*Florida (USA)*	*Texas (USA)*	*California (USA)*
1. Clearly defined boundaries	Regional management groups	Epidemiological Phytosanitary Management Areas (AMEFIs)	-	Citrus Health Management Areas (CHMAs)	Citrus Pest and Disease Management Zones	Psyllid Management Areas (PMAs) or Pest Control Districts (PCDs)
2A. Congruence between rules and local conditions	AWM rules defined by the local citrus industry	AWM rules defined by national plan	AWM rules not available	AWM rules defined by growers in collaboration with University of Florida (UF-IFAS)	AWM rules defined by growers in collaboration with Texas A&M University	AWM rules defined by the local citrus industry with advice from University of California (UC). Some pre-existing PCDs
2B. Congruence between appropriation and provision rules	AWM funded by individual growers	Insecticides supplied by government to non-autonomous AMEFIs	ACP control funded by individual growers	AWM funded by individual growers	AWM funded by individual growers. Assessments to the TCPDMC based on acreage	AWM funded by individual growers. Other HLB assessments based on production volume or acreage
3. Collective-choice arrangements	AWM organized locally through Fundecitrus. Other HLB rules defined at national level in consultation with Citrus Sectorial Chamber	AWM organized at national level	AWM not available. Other HLB rules defined at national level in consultation with Inter-institutional Coordination Unit	AWM organized by growers in collaboration with UF-IFAS	AWM organized by the Texas Citrus Pest and Disease Management Corporation (TCPDMC)	AWM organized locally through PCDs or PMAs. Citrus Pest and Disease Prevention Committee (CPDPC) establishes rules for HLB in collaboration with CDFA

4A. Monitoring users	No	Monthly reports of area treated coordinately	-	No	Reports of area treated coordinately after each treatment	Seasonal reports of area treated coordinately
4B. Monitoring the resource	Phytosanitary Alert System by Fundecitrus	Diaphorina Monitoring System (SIMDIA)	Monitoring by citrus industry and Argentine National System for Surveillance and Monitoring (SINAVIMO)	Florida Department of Food and Agriculture (FDACS) with federal funds from Citrus Health Response Program (USDA-CHRP)	ACP monitoring program by TCPDMC. Scouts hired by TCPDMC and growers	ACP monitoring by CDFA, County Agricultural Commissioners (CACs), Citrus Research Board (CRB) and pest control advisors (PCAs) hired by growers
5. Graduated sanctions	No	No	No	No	No	No
6. Conflict-resolution mechanisms	-	-	-	-	-	No, but Task Force meetings and other public meetings have been used for addressing conflicts
7. Minimal recognition of rights to organize	Fundecitrus	AMEFIs and State Plant Health Committees established by the government, but with grower leaders and citrus industry representatives	Federación del Citrus de Entre Ríos	CHMAs imposed on growers, but use of a grower leader	TCPDMC	CPDPC, PCDs, grower leader in PMAs
8. Nested enterprises	Yes	Yes	Yes	Yes	Yes	Yes

Note: The symbol "-" indicates that there is not enough information available to determine whether the design principle is present or not. Information retrieved from Brazil (Fundecitrus 2020a; MAPA 2020), Mexico (SENASICA 2019b, 2019a), Argentina (SAGPyA 2009, 2018), Florida (FDACS 2016; National Research Council 2010), Texas (TCPDMC 2020a) and California (CDFA 2019).

DP1: Clearly defined boundaries

Clear user and resource system boundaries exist for AWM of ACP in Brazil, Mexico, Florida, Texas and California. In Brazil, growers formed voluntary groups to coordinate AWM of ACP (Belasque Junior et al. 2009). Additionally, some large citrus operations have provided citrus health services beyond their boundaries, spraying homeowner citrus trees monthly and offering to replace them with other fruit trees (Johnson and Bassanezi 2016). The Mexican government defined the boundaries of ACP management areas based on HLB incidence, ACP prevalence, citrus acreage, climatological conditions and geographical barriers (SENASICA 2012). In Florida, growers were asked to voluntarily coordinate treatments over areas that were designed to achieve local ACP population suppression (Rogers 2011). Texas citrus growers established pest management zones within which every grower is required to treat in coordination (TCPDMC 2020a). In California, AWM is organized through Psyllid Management Areas (PMAs) and Pest Control Districts (PCDs). PMAs are voluntary groups of 25-35 neighboring growers who coordinate insecticide applications over 2-3 weeks (Grafton-Cardwell et al. 2015). PCDs are special districts formed by growers to have the legal authority to enforce control measures against pests affecting a specific crop (UCCE 2005).

DP2: Congruence between appropriation and provision rules and local conditions

Congruence between rules and local conditions (DP2A) is hard to achieve under *top-down* approaches if plant health rules for an entire country do not account for local circumstances and stakeholders' attributes. In Brazil, a national law requires the removal of symptomatic trees, but AWM rules are defined by the citrus industry (Belasque Junior et al. 2009). In Mexico, national citrus health rules are enforced by federal and state authorities (FAO 2013; SENASICA 2019a). In Argentina, there is a national plan for HLB, but rules are established in consultation with the state authorities and the citrus industry (SAGPyA 2009). In the US, the NPPO provides oversight and funding, regulates the movement of plant material between states, and certifies diagnostic protocols (USDA-APHIS-PPQ 2019). However, citrus health rules differ among states (Graham et al. 2020), and rule enforcement differs by county within states.

Congruence between appropriation and provision rules (DP2B), *i.e.* an alignment between who funds citrus health efforts, who implements them and who benefits from them, varies between regions. National funds collected through taxes are used to manage HLB everywhere, but the citrus industry is also providing funds, mostly for monitoring. In Texas, monitoring efforts are funded through assessments collected per acre (TCPDMC 2020a). In California, the state-wide HLB response is funded through assessments collected at an agreed rate on each carton of citrus fruit harvested, and PCD assessments are collected per acre. Details of the funding arrangements are not available for other regions. Insecticide treatments are paid individually by growers in every region except Mexico, where the federal government supplies insecticides to most management areas (SENASICA 2019a).

DP3: Collective-choice arrangements

Evidence of grower participation in rule-making for citrus health at the local level is not available for most regions. A Citrus Sectorial Chamber in Brazil and an Inter-institutional Coordination Unit in Argentina –composed of representatives of the citrus industry, the NPPO, state authorities and scientists meet periodically to review the status of the HLB epidemic and recommend actions to be regulated (MAPA 2020; SAGPyA 2009). In Texas, a non-profit organization funded by the citrus industry plans and operates the AWM program (TCPDMC 2020a). In California, the State program for HLB is led by a committee of citrus industry representatives, which discusses rules in public meetings, approves them by vote, and enforces them through an agreement with the

California Department of Food and Agriculture (CDFA). At the local level, growers choose to coordinate through PMAs, which are voluntary; or PCDs, which are established by a majority vote (≥51% of acreage) and are subject to the rules defined by the elected PCD board of directors (UCCE 2005).

DP4: Monitoring

Monitoring growers (DP4A) for compliance with AWM occurs in Mexico, where state coordinators report monthly treated area relative to area targeted for treatment (SENASICA 2019b) and Texas, where scouts hired by the state program call growers after the AWM treatments to record the percentage of the acreage that was treated coordinately (Sétamou, pers. comm.). In California, regional coordinators track the acreage that was treated under coordination through pesticide use reports. Coordinators have close ties with the citrus community and are accountable to the grower committee.

Monitoring ACP populations (DP4B) is done everywhere to enable better timing of insecticide applications. In São Paulo, the monitoring program is led by the citrus industry (Fundecitrus 2020b). In Mexico, a technical working group within each state monitors ACP populations and determines when to spray (SENASICA 2019a). In Argentina, ACP monitoring is part of a national surveillance system, but also involves the citrus industry (ACC 2018). In Florida, federal and state authorities monitor ACP populations and the University of Florida suggests treatment times (Rogers et al. 2010). In Texas, the industry organization hired scouts to monitor the ACP population and citrus flush (new foliar growth) to time treatments (Sétamou 2020). In California, CDFA, county authorities, grower organizations and advisors hired by the growers cooperatively monitor ACP populations, and treatments are decided by local task forces or PCDs in consultation with the University of California. Real-time ACP population data are published online in Brazil, Florida and Texas (Fundecitrus 2020c; TCPDMC 2020b; UF-IFAS 2018).

DP5: Graduated sanctions

Sanctions on growers who do not comply with citrus health rules are not common. In Brazil, growers who do not inspect regularly and remove infected trees are subject to fees (MAPA 2008), but they are not sanctioned for non-compliance with AWM. California has opted to incentivize compliance instead of sanctioning. If 90% of the acreage in a PMA or PCD is treated within a specific time frame, the CDFA will treat nearby residential areas if given consent by homeowners (CDFA 2019). In some of the PCDs, if growers cannot prove compliance with AWM they do not receive reimbursement of PCD assessments. The board of directors of the PCD has the right to enter their property and treat on their behalf, billing them later.

DP6: Conflict-resolution mechanisms

We found no reference to conflict-resolution arenas in any of the areas. In California, CPDPC, PCD and Task Force meetings are public, providing a potential arena for discussing conflicts over provision of citrus health.

DP7: Minimum recognition of rights to organize

Stakeholder rights to devise institutions to ensure citrus health under HLB have been recognized in all areas. In São Paulo, AWM for ACP is coordinated by Fundecitrus, an association funded by growers and juice manufacturers (Bassanezi et al. 2013). In Mexico, the committees that coordinate efforts at the state level already existed for other crops. Although ACP management areas were imposed on the citrus growers by federal or state authorities in Mexico and Florida, they rely on local leaders to coordinate efforts (Rogers 2011; SENASICA 2019a). In Texas, the citrus industry voted to establish the Texas Citrus Pest and Disease Management Corporation, which was authorized to lead the HLB response under the supervision of the Texas Department of Agriculture (TCPDMC 2020a). Similarly, a committee composed of elected industry representatives leads the HLB response in California in collaboration with CDFA. At the local level, growers have the right to decide whether to coordinate through PMAs or PCDs.

DP8: Nested enterprises

Because HLB is an invasive disease that can spread quickly over different jurisdictions, international guidelines stress the importance of coordinating activities across institutional scales. NPPOs have established a national plan that is implemented by State authorities through coordination with regional authorities and collaboration from the citrus industry. However, the governance network is adapted to each area, and cross-scale interactions vary. For instance, Brazil and Florida rely on local organizations to coordinate AWM, while federal and state organizations monitor or enforce regulations. In contrast, Mexico, Argentina, Texas and California state-level committees coordinate HLB management, gathering local information to transmit to the higher scales while orders and funds are transferred from the national and state authorities to the local scales.

Implications of Ostrom's design principles for plant health

With the increasing global threat to food security from plant pests and diseases, there is a need to better understand what institutional approaches might be more appropriate for provision of plant health in different social-ecological systems. This will only be achieved by examining the performance of institutions in different contexts and developing a theory of when particular institutional arrangements seem to lead to better ecological and social outcomes (Epstein et al. 2015). We chose to focus on HLB because it is a well-documented example of an invasive disease that is threatening citrus production worldwide and has triggered parallel responses amid different ecological and social contexts, but a similar approach could be employed for other plant diseases that are threatening food security in other parts of the world. As observed with RTD (Cabunagan et al. 2001) and recently with CBSD (Legg et al. 2017), epidemiological studies have proven that collective action is key to limiting HLB spread and ensuring citrus health (Bassanezi et al. 2013). Consequently, institutional arrangements were made following international guidelines to promote AWM of ACP and ensure *ecological fit* between institutions and the spatial and temporal dynamics of HLB. Fewer recommendations were made to ensure *social fit* between institutions and the societies affected.

Using Ostrom's DPs as a diagnostic tool to examine plant health institutions across different geographical areas is a necessary step towards applying collective action theory to plant health governance in order to improve *social fit*. Our study shows that Ostrom's DPs have been incorporated in all HLB-affected areas' institutions, suggesting implicit recognition of the collective action problem associated with citrus health provision, even though there is no evidence that it was explicitly considered. Because the DPs reduce the transaction costs of searching for mutually beneficial solutions; bargaining over the costs and benefits of those solutions; and monitoring and enforcing management actions (Wilson et al. 2013), collective action theory predicts that citrus-growing areas that incorporate more DPs will be more effective in engaging affected communities, promoting self-organization, and securing participation in AWM that ultimately helps slow HLB spread. These concepts seem to be general enough that they can be expected to apply to a wide range of plant health threats.

Indeed, the apparent relationship between DPs, as implicitly understood and operationalized on an *ad hoc* basis, and plant health provision suggests the DPs might be a useful reference to improve *social fit*, and consequently *social-ecological system fit* (Epstein et al. 2015). For example: HLB was first detected in Brazil and Florida, and the epidemics have followed very different trajectories. In Brazil, the citrus industry self-organized through Fundecitrus and is leading the AWM program, fulfilling most of Ostrom's DPs. In the states of São Paulo and Minas Gerais, the percentage of HLB-positive orange trees has stabilized around 18% and citrus production survives at a profitable level (Bassanezi et al. 2020). This "success" is commonly attributed to the large size of citrus operations and the adoption of control measures as soon as HLB was detected, fostered by a national law that required surveying and removing infected trees (Bové 2012). By contrast, many growers in Florida were reluctant to voluntarily remove infected trees and, despite ACP control, HLB spread quickly to 12 counties in 2 years (Bové 2012; Shimwela et al. 2018). ACP management areas defined by experts set clear boundaries for collective action (DP1), but growers lacked experience in coordinating activities (no DP2A or DP7), participation was not monitored (no DP4A), sanctions were not imposed on noncompliant growers (no DP5), and there was no state-level industry-led organization coordinating efforts (no DP8). A recent study concluded that the AWM program in Florida has been unsuccessful and highlighted the need for alternative institutional arrangements (Singerman and Rogers 2020).

In Mexico, Texas, California and Argentina, HLB was detected later, so institutional arrangements benefited from the experience acquired in Brazil and Florida. In Mexico, 26% of the commercial citrus acreage is affected by HLB and AWM programs are ongoing in 24 states, with some successful cases (Martínez-Carrillo et al. 2019). ACP management areas (DP1) were designed based on epidemiological criteria, but they are coordinated through state committees that already existed (DP7, DP8). The government supplies insecticides to the growers and tracks participation in AWM (DP4A), and workshops are held regularly to raise awareness and promote participation.

In Texas, the AWM program is led by the citrus industry (DP3, DP7). AWM zones (DP1) were established by an industry-led organization that collects assessments per acre (DP2B), runs an ACP monitoring program (DP4B), and tracks participation in AWM (DP4A). Although participation has increased over time, a favorable climate and the abundance of residential citrus trees have fostered HLB spread throughout the state, and the disease is now established. However, citrus yields have not declined dramatically and the AWM program continues, adapting to the new conditions (Graham et al. 2020).

In California, HLB has progressed very slowly and is still confined to residential properties in 4 counties 8 years after first detected. Although this is due to a complex mixture of factors, the institutional arrangements for citrus health under HLB follow Ostrom's DPs remarkably closely. Acceptance of self-imposed regulations by the citrus industry, continuous interactions with the scientific community for policy guidance (McRoberts et al. 2019), and resources targeted for HLB detection, along with California's Mediterranean climate, have all probably limited HLB spread. Nevertheless, HLB-positive trees are detected every week and ACP is established in southern California, where participation in AWM has been uneven. Interdisciplinary research is needed to identify barriers to collective action, because a *C*Las-positive ACP was just detected in commercial groves (CPDPP 2020) and *C*Las-positive trees might be detected soon.

In Argentina, HLB has only been detected in a few towns and ACP is not widespread, so AWM has not been fully implemented (SENASA 2020). Early monitoring efforts, heavy involvement of the citrus industry in management activities (DP2, DP3, DP7, DP8), and learning from other regions might help facilitate collective action.

To show how this diagnostic approach could be applied to other diseases, we retrieved information about the institutional arrangements for RDT management in Southeast Asia (Table 1.3) and found that most of Ostrom's principles were not part of the area-wide synchronous rice planting programs that were implemented in the 1970s and 1980s. As in the HLB case, an area-wide approach was strongly recommended by international guidelines (Brader 1979), and many countries implemented national programs to promote its adoption, but in this case, they were heavily based on a *top-down* approach (Litsinger 2008). Synchronous planting was imposed by government agencies within designated ~1000 ha blocks (DP1) through law enforcement and sanctions to noncompliant growers, who in many cases were not used to coordinating activities with field neighbors (no DP2), so grower organizations and collective-choice arrangements were scarce (no DP3, no DP7) (Goodell 1984; Loevinsohn et al. 1993). Due to the dependency of rice planting on water availability, *top-down* success cases such as the Muda irrigation scheme in Malaysia required investment by the government in irrigation infrastructures, mechanized plowing, timely credits and close supervision of grower groups (Goodell 1984). Still, success was conditioned by the collective action problem associated with water management, itself requiring complex institutional arrangements (Johnson and Handmer 2003). Alternatively, the *subaks,* local water-user groups in Bali (Indonesia), provided an example of *bottom-up* institutional arrangements that had evolved over centuries of rice cultivation to optimize pest and water management (Lansing et al. 2017, Lansing 1991).

Table 1.3: Presence of Ostrom's "Design principles illustrated by long-enduring CPR institutions" in the institutional arrangements for rice health under rice tungro disease (RTD) in Southeast Asia and cassava health under cassava brown streak disease (CBSD) in East Africa.

Design principle	RTD	CBSD
1. Clearly defined boundaries	Irrigation blocks of 1000-2000 ha, considering vector dispersal range (Loevinsohn et al. 1993)	Two study areas in different parts of Tanzania chosen by researchers based on importance of cassava to the communities and relative CBSD severity (Legg et al. 2017)
2A. Congruence between rules and local conditions	Coordination required for synchronous planting is similar to coordination required for water management, but rice irrigation systems favor asynchronous planting (Goodell 1984)	One-year long period of sensitization with farmers, research institutions, non-governmental organizations and extension services prior to community phytosanitation study. Local leaders raised awareness about the initiative (Legg et al. 2017)
2B. Congruence between appropriation and provision rules	Mostly *top-down* programs with government funding (Litsinger 2008)	Study conducted with grant funding. Removal of all existing cassava plants by community members. Provision of disease-free cassava planting material by the research team. Free maize seed and sweet potato planting material supplied as an incentive for compliance (Legg et al. 2017)
3. Collective-choice arrangements	No evidence in most areas, except for some irrigator associations in the Philippines (Goodell 1984).	Farmers removed plants in existing cassava fields, and the process was supervised by local task forces
4A. Monitoring users	In some studies, the percentage of rice area planted synchronously was monitored by researchers (Sama et al. 1991)	Local task forces composed of extension workers and farmer representatives ensured that farmers did not plant local varieties and removed plants that showed CBSD symptoms (Legg et al. 2017)
4B. Monitoring the resource	Not recommended. Studies suggested that monitoring the vector population was not useful to predict RTD epidemics (Chancellor et al. 1996)	Community members monitored the fields and removed symptomatic plants. Researchers collected vector, disease and harvest data for the study (Legg et al. 2017)
5. Graduated sanctions	The Malaysian government threatened to withhold irrigation from growers that were late in following the recommended planting dates	-

6. Conflict-resolution mechanisms	-	-
7. Minimal recognition of rights to organize	Asking rice field neighbors to collaborate was problematic, because groupings of rice growers in Southeast Asia tended to be based on residential neighborhood proximity or kinship, not rice field proximity. Only in some areas there was a precedent for collaboration through irrigator associations (Goodell 1984)	-
8. Nested enterprises	-	National Cassava Steering Committees created to bring together stakeholders involved in cassava production, including the ministries of agriculture and cassava traders. The committees serve as coordination networks and they regulate the movement of planting materials (FAO 2013a)

Note: The symbol "-" indicates that we could not find enough information to determine whether the design principle is present or not. Specific sources of information are indicated in the table.

In Central and East Africa, international guidelines have also promoted the implementation of "community phytosanitation" to ensure cassava health in CBSD endemic areas, but few recommendations have been made in terms of the institutional arrangements that could favor collective action (Legg et al. 2014). In line with Ostrom's principles, the guidelines recognized that local communities that are currently affected by CBSD, or could potentially be affected, would have to establish and implement community-based regulations and by-laws (Legg et al. 2014). A recent study provided an example of how this type of approach could be implemented through local task forces (DP3) and community monitoring (DP4), but more work will be needed to scale it up (Legg et al. 2017). Our hope is that this analysis will point towards possible approaches to favor *bottom-up* initiatives within cassava-dependent communities in Africa.

DISCUSSION

Our analysis suggests that Ostrom's DPs are a valid reference to promote collective action for plant health provision, but more work is needed to establish relationships between institutional arrangements and plant health outcomes. In the same way that the DPs were deduced from case studies of CPRs, further examination of plant health institutions should lead to identification of more tailored design principles. In our case studies, we observed that conflict-resolution arenas, monitoring of compliance with AWM and graduated sanctions on non-compliant growers are not common, which is consistent with previous studies that suggested that not all of Ostrom's design principles might be as important for plant health provision as for CPRs (Graham et al. 2019; Kruger 2016). The need to prevent *over-exploitation* in CPRs might call for institutions that are not essential for plant health, where the need is to ensure provision of the public good.

Turning to specific methodological needs, institutional studies could be complemented with social and ecological studies to better understand the advantages and disadvantages of *top-down* vs. *bottom-up* approaches to plant health in different social and ecological contexts.

Participatory studies and surveys could provide insight into the attitudes and norms that drive collective action in societies facing plant health threats (Mankad and Curnock 2018) and improve our understanding of the role of social learning and communication (Damtew et al. 2020; Nourani et al. 2018). Agent-based model simulations could be used to estimate the economic benefits of collective plant health provision in different landscapes (Rebaudo and Dangles 2011), which would help characterize the collective action problem from a game theoretical perspective and point towards potential institutional arrangements (Bodin 2017).

Beyond the individual and regional scales, network analysis could be used to evaluate if there is an alignment between the governance network that has been built in response to a plant health threat and the characteristics of the ecological and social systems governed (Lubell et al. 2017; McAllister et al. 2015). This type of analysis would bridge the gap between social network analysis and network approaches taken by ecologists and plant pathologists (Garrett et al. 2018), advancing the integration of social and ecological networks studies of how societies face emerging threats (Barnes et al. 2019).

We hope this study has illustrated the potential of addressing plant health provision as a collective action problem, within a social-ecological systems framework that gives equal research priority to ecological and social systems (Ostrom 2009). Only an interdisciplinary research agenda will allow us to establish the link between institutional approaches and outcomes, and determine which institutions will be more robust to facilitate collective action and ensure plant health to achieve global food security.

CONCLUSIONS

Although the social and economic dimensions of plant health have received increasing attention in recent years, incorporating them into the design of plant health institutions to improve *social-ecological system fit* is still a challenging interdisciplinary frontier. With the increasing global spread of plant pests and diseases, there is a need to better understand the collective action problem associated with plant health provision, and how to combine institutional approaches along the *top-down* to *bottom-up* continuum to ensure the sustainability of food production. This need is particularly urgent in the case of HLB, which is threatening the future of citrus production worldwide, but it is also a persistent necessity to ensure food security in developing countries. Our hope is that this study will show the potential of bringing collective action theory to plant health governance to mitigate the impact of HLB and other damaging diseases.

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Chapter 2:

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

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.

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 chapter 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" (CLas), 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 CLas-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 CLas 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 CLas 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 2.1). 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).

Table 2.1: 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.

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= 2.84x10^{-14}) and older participants tended to manage smaller groves (ρ= -0.27, P= 7.04x10^{-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 $P\ (Y > \textit{maybe}) = 1 - P\ (Y \leq \textit{maybe})$ (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 ($P = 3.54 \times 10^{-7}$ for the Kruskal-Wallis test), and pairwise comparisons between regions showed that there was a significant difference between the Valley and the Coast ($P = 2.74 \times 10^{-7}$ for the Wilcoxon-Mann-Whitney test) and between the Valley and SoCal ($P = 4.71 \times 10^{-5}$). 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 (Figure 2.1, Supplementary Table 2.1). 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.

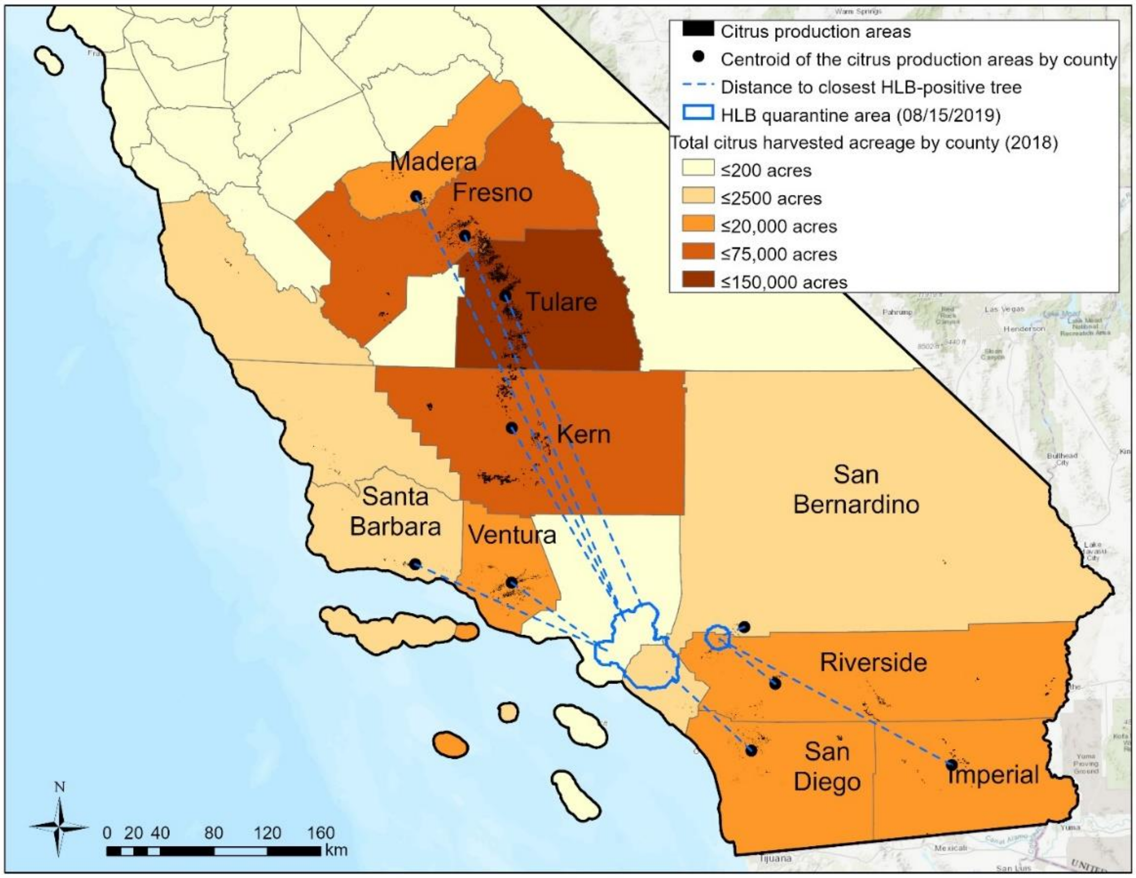

Figure 2.1: Distance from the centroid of the citrus acreage in each county to the closest HLB-positive tree detected by CDFA. The areas shaded in black represent the citrus production areas according to the Citrus Research Board (CRB) database (R. Dunn, *personal communication*). The black dots represent 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 2.1). 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).

In addition, we calculated the correlation between distance to confirmed HLB positive trees and propensity to adopt the practices recommended by the CPDPC (Table 2.2).

Table 2.2: 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 Figure 2.1).

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

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 (Figure 2.2). 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.

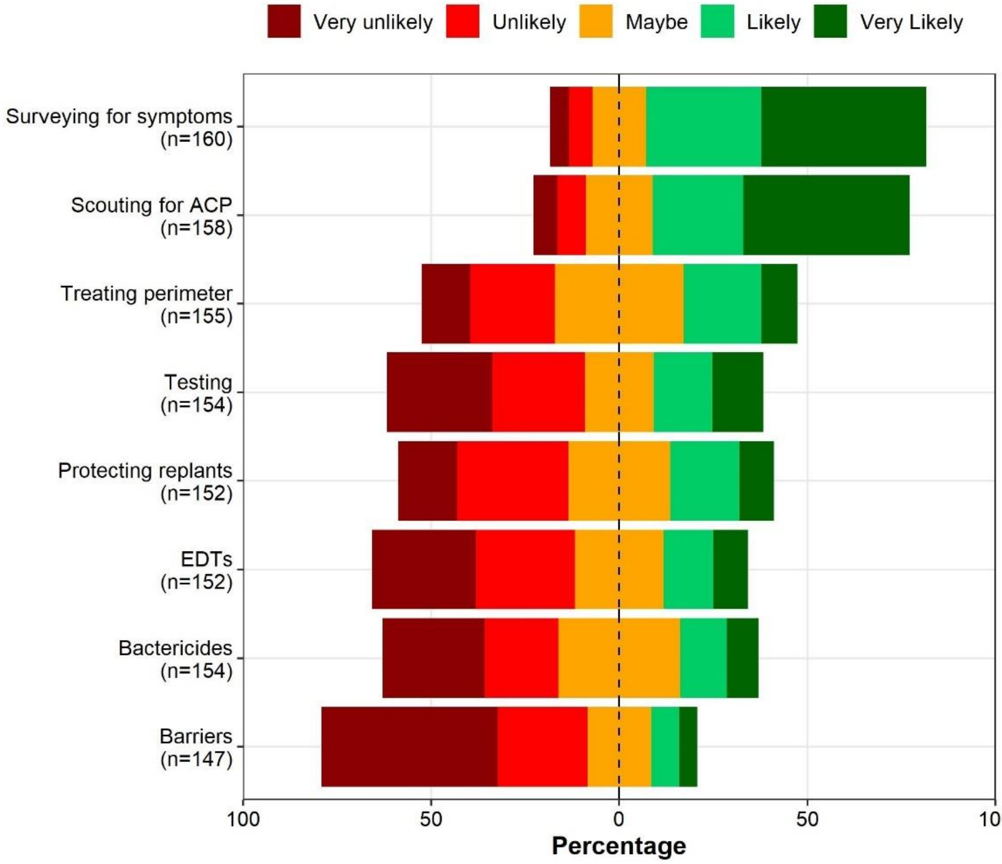

Figure 2.2: Reported propensity to adopt the best management practices for HLB. The practices assessed in the survey are shown on the y axis, ordered from highest (top) to lowest (bottom) percentage of *likely* and *very likely*. The percentage of responses to each question was calculated on a total 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.

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 2.2). 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 ($P < 2.2\text{x}10^{-16}$), 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 (Figure 2.3, Supplementary Table 2.3).

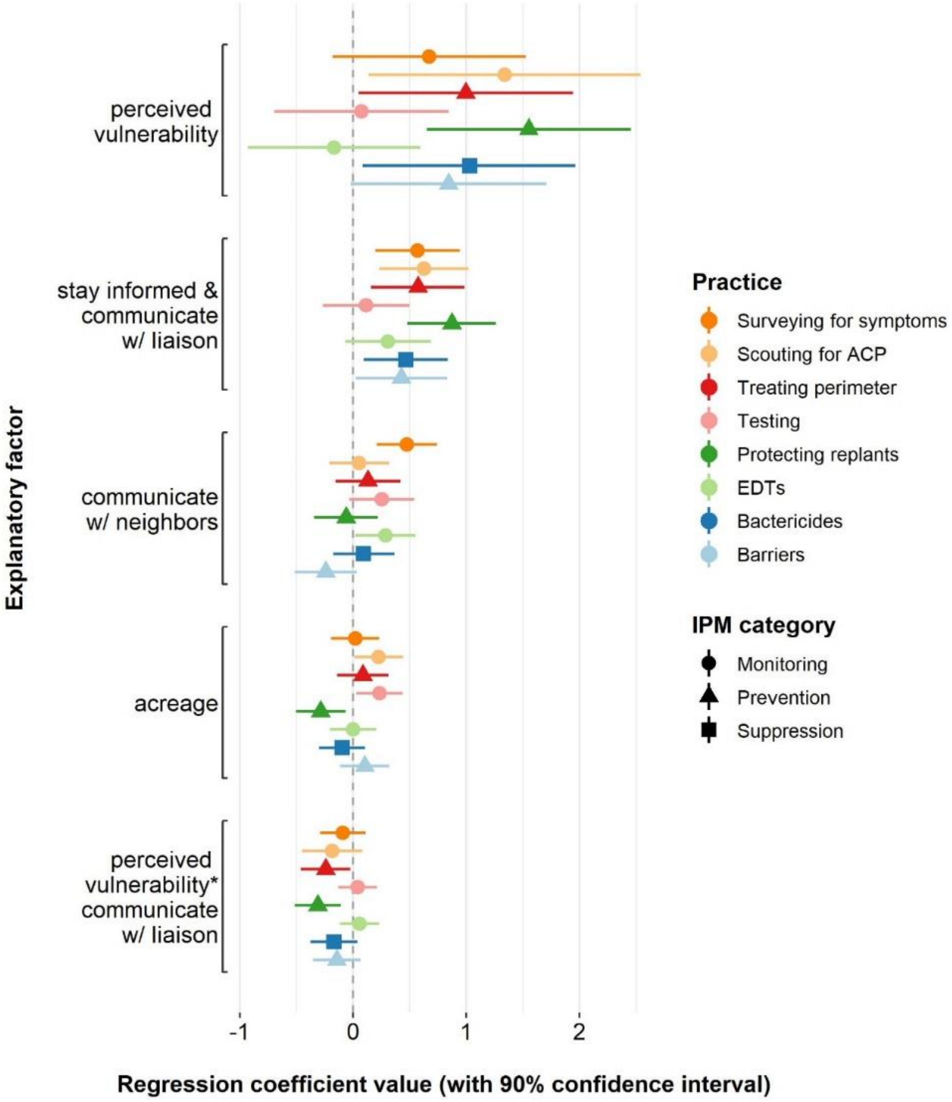

Figure 2.3: Confidence intervals of the regression coefficients estimated by the multivariate ordinal regression model. The x axis represents the values of the regression coefficients. The y axis identifies the explanatory factor that the coefficients correspond to. The symbols correspond to the value 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 Figure 2.2.

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 (Figure 2.3). 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 Figure 2.4 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.

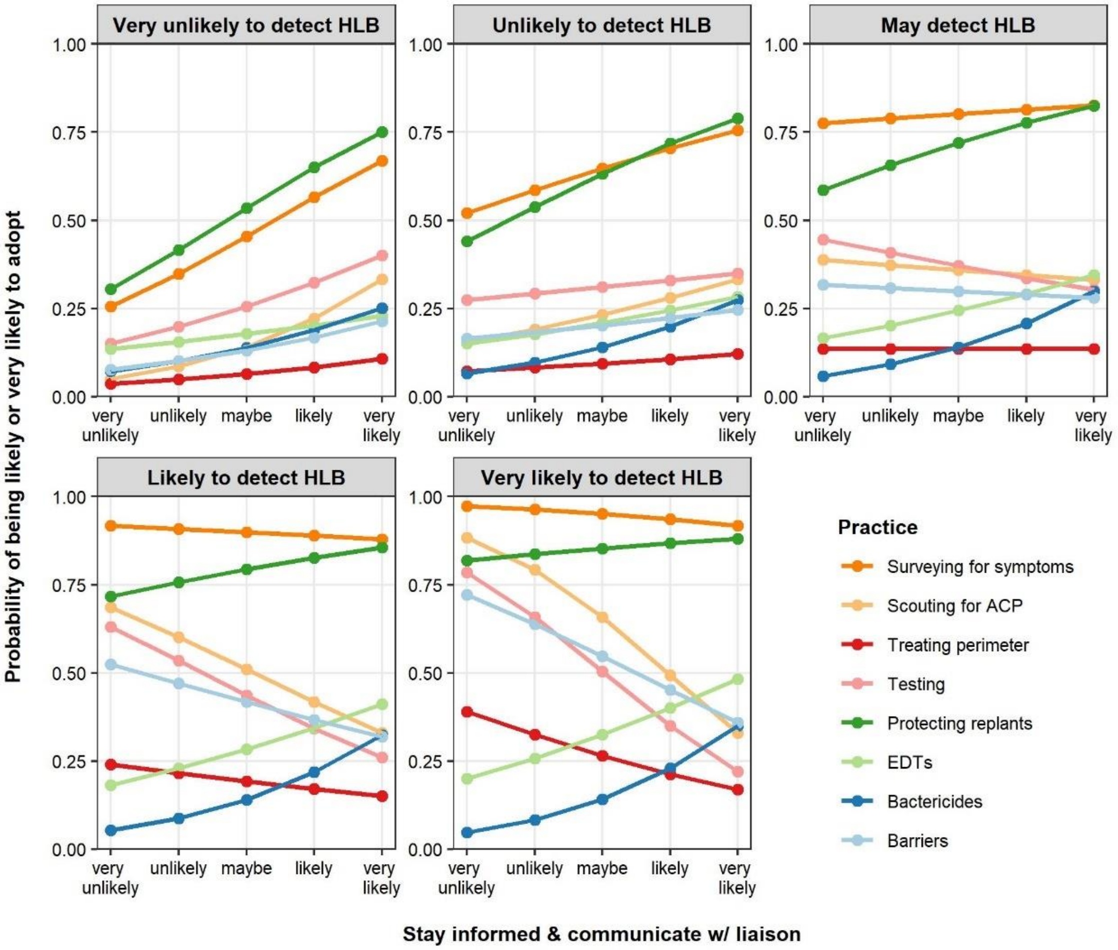

Figure 2.4: Probability of being *likely* or *very likely* to adopt the best management practices for HLB according to the perceived vulnerability to HLB and the propensity to stay informed and communicate with the grower liaison. The practices were colored according to the legend on the right.

For example, in the top left panels in Figure 2.4, 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 2.4). 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 (Figure 2.5, Supplementary Table 2.5), 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 (Figure 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 (Figure 2.5). 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 CLas 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.

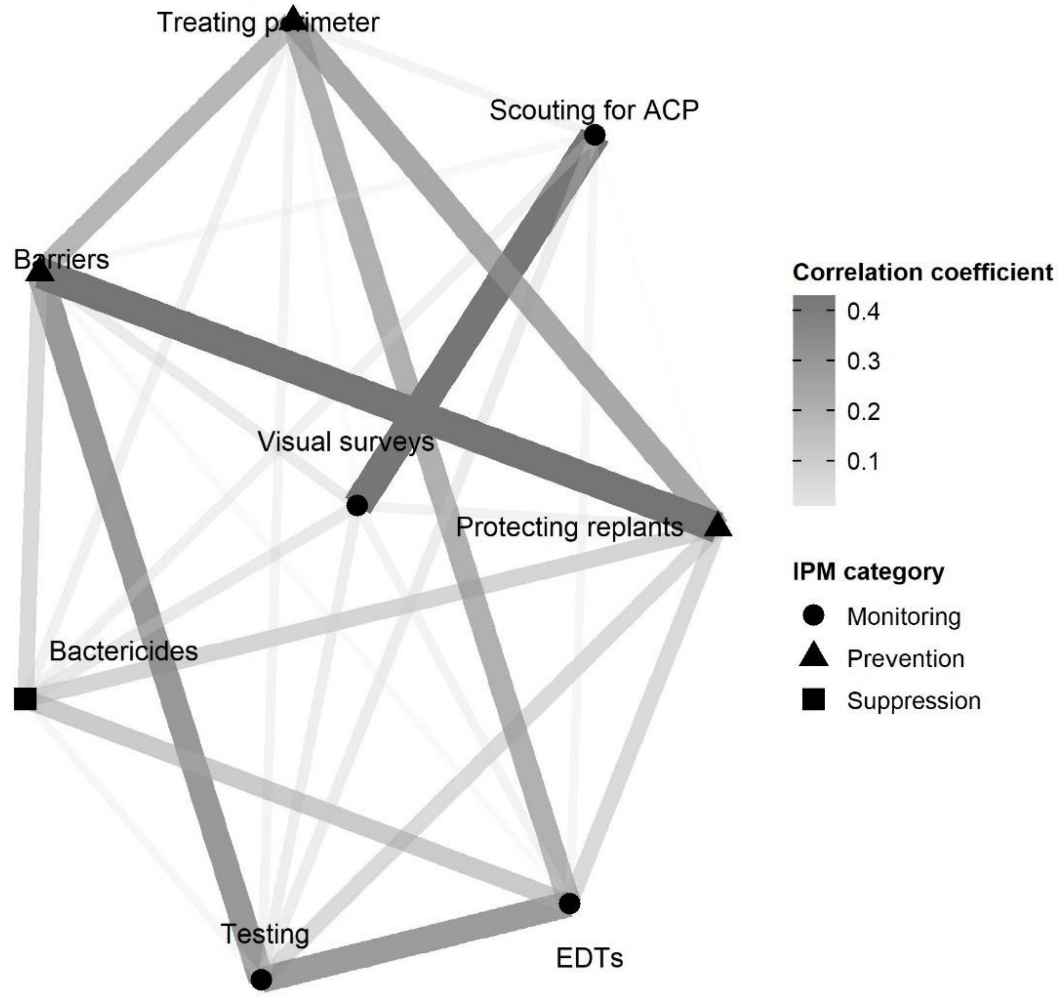

Figure 2.5: Interdependence in the propensity to adopt the best management practices for HLB, as estimated by the multivariate ordinal logistic regression model. The nodes in the network correspond to each practice, with different shapes for the integrated pest management (IPM) category each practice 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 2.5).

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 CLas-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 CLas 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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SUPPLEMENTARY MATERIALS

Supplementary text 2.1: 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 2.1: 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)	Min. distance from groves (km)	Max. 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 2.2: 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 2.3: 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 2.4: 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.

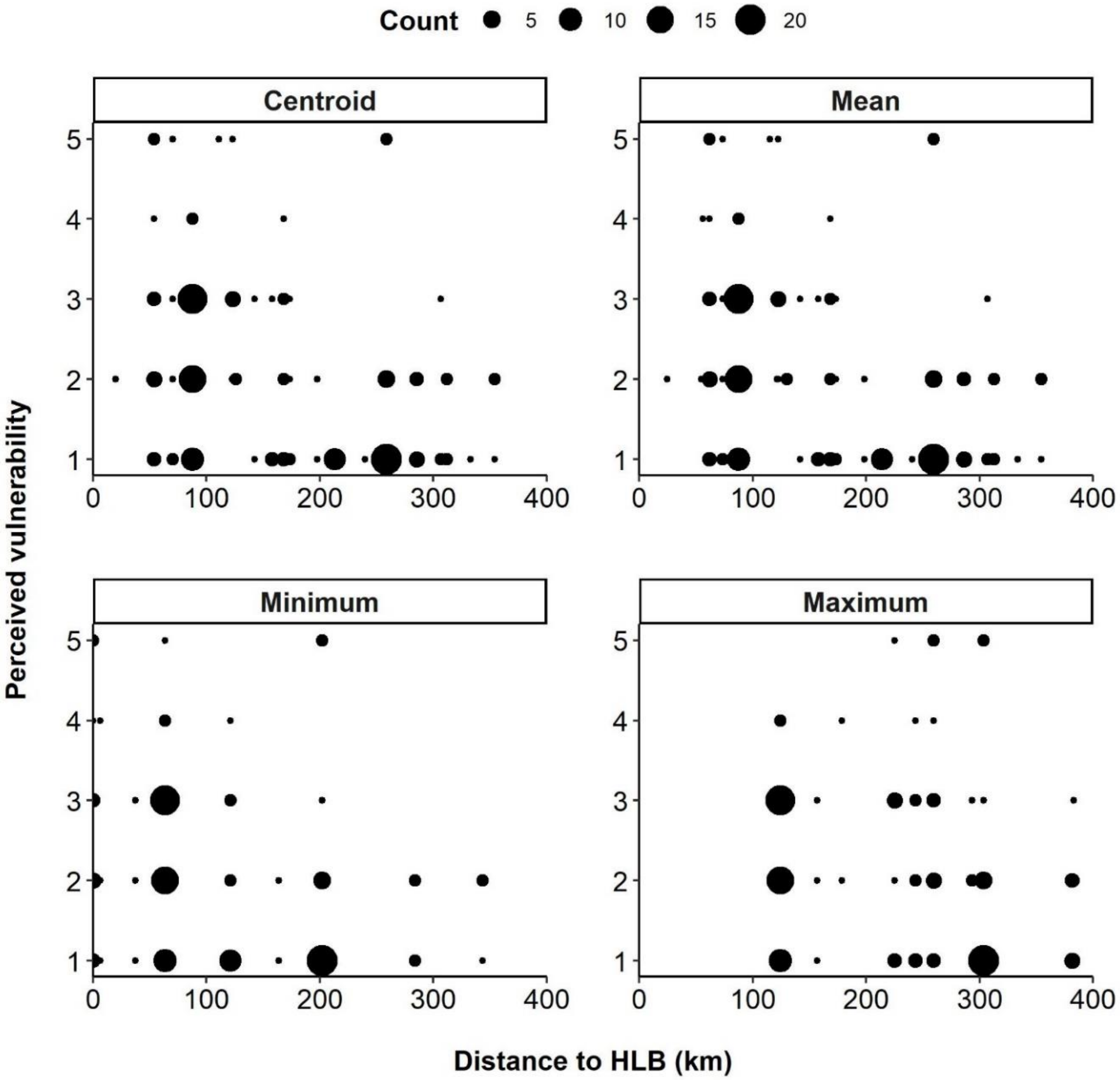
	Scouting for ACP	**Treating perimeter**	**Testing**	**Protecting replants**	**EDTs**	**Bactericides**	**Barriers**
Surveying for symptoms	0.375** (0.119)	0.098 (0.146)	0.054 (0.14)	0.124 (0.144)	0.033 (0.149)	0.144 (0.135)	-0.007 (0.145)
Scouting for ACP		0.017 (0.138)	0.056 (0.143)	0.083 (0.143)	0.018 (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

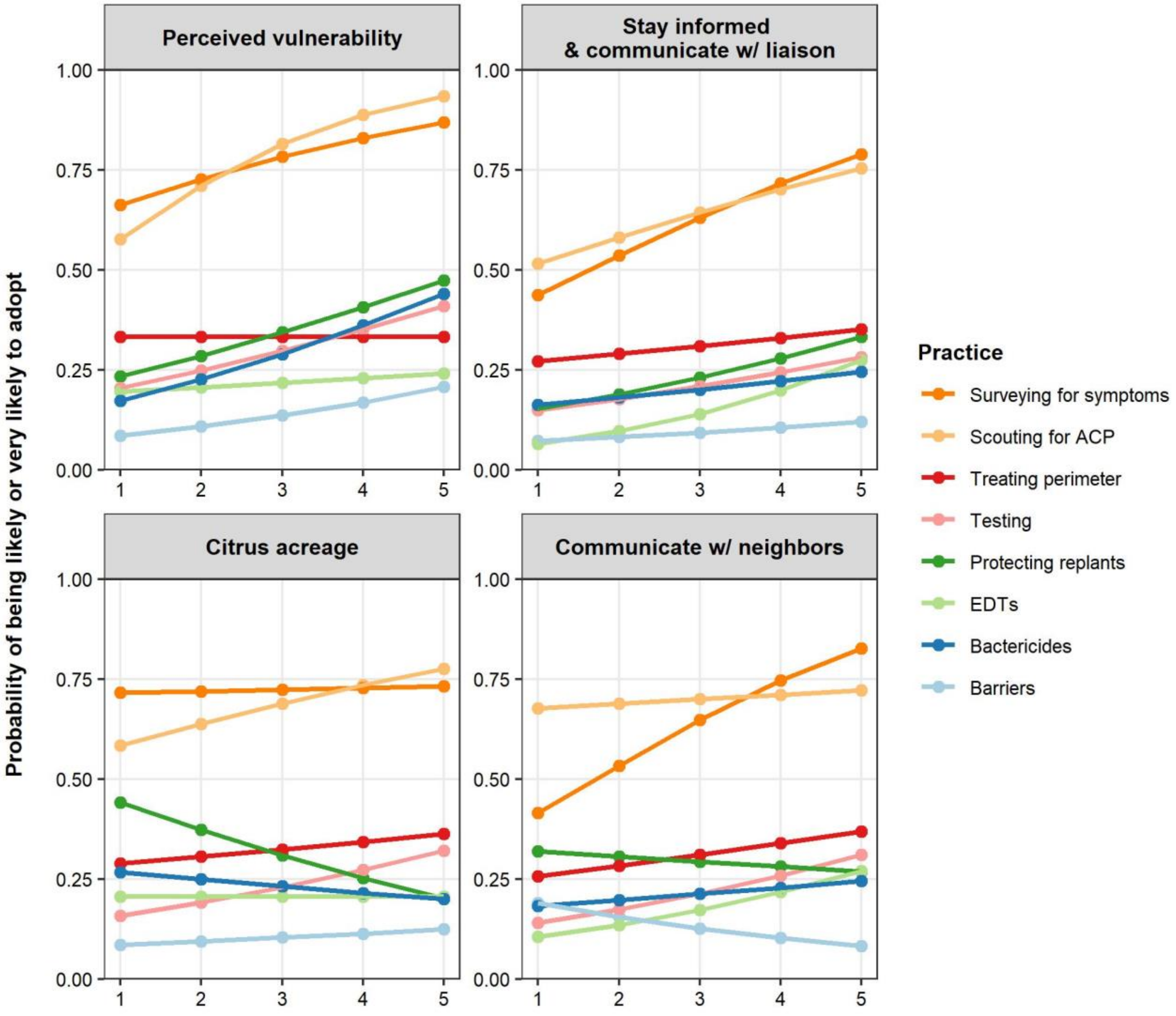
Supplementary Table 2.5: Correlation between the propensity to adopt HLB management practices (Spearman's rank correlation coefficients)

	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 2.1: 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 2.2: 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.

Chapter 3: Individual perceptions and group-level determinants of collective action in the area-wide management of an invasive plant disease

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. We contribute to the emerging application of collective action theory to invasive species management by analyzing the AWM strategy for huanglongbing (HLB) disease of citrus in California. To coordinate insecticide treatments for the vector of HLB and foster collective action, citrus stakeholders have adopted two distinct institutional approaches: Psyllid Management Areas (PMAs), in which treatments are voluntary, and Pest Control Districts (PCDs), in which 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 these institutional approaches, individual perceptions and group-level determinants have had on collective action. Our results show that although citrus stakeholders are convinced of the benefits of AWM, they are aware of the collective action problem associated with it. Most survey participants identified the lack of participation as the main barrier to AWM, and a quarter did not believe that their neighbors would contribute. The size of the group, the average size of citrus groves and the heterogeneity in grove size were identified as group-level determinants that may hinder 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 factors that may enable and sustain collective action for invasive species management.

INTRODUCTION

In recent years, there has been a growing interest in the collective action problem associated with the management of invasive species (Bagavathiannan *et al.*, 2019; Garcia-Figuera *et al.*, 2021b; Graham *et al.*, 2019). As international trade networks have become more dense, invasive species have become a global problem that threatens the sustainability of a wide range of social-ecological systems (Bebber *et al.*, 2014; Driscoll *et al.*, 2014; Faulkner *et al.*, 2020; Freer-Smith and Webber, 2017; Simberloff *et al.*, 2013). Although invasive species spread across property and jurisdictional boundaries, traditional management strategies have focused on individual property solutions imposed through *top-down* regulations, with few examples of collective approaches to invasive species management that have transcended such boundaries (Epanchin-Niell *et al.*, 2010; Graham, 2013). 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 are mostly non-rivalrous (Graham *et al.*, 2019; Niemiec *et al.*, 2020). Despite the differences between public goods and common-pool resources (CPR), the conceptualization of invasive species management as a collective action problem has drawn attention to the potential of applying collective action theory originally deducted from case studies of CPRs (Baggio *et al.*, 2016; Ostrom, 1990) to the management of invasive species (Graham *et al.*, 2019).

However, applications of collective action theory to the management of invasive plant pests and diseases are still limited. From an ecological perspective, *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 a high dispersal potential (Hendrichs *et al.*, 2021; Vreysen *et al.*, 2007). 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 from a social perspective (Kruger, 2016; Mankad *et al.*, 2017).

AWM is the main strategy for huanglongbing (HLB), an invasive disease of citrus trees that is threatening citrus production worldwide (Wang, 2019). HLB was originally described in Asia (Lin, 1956) and it spread to the main citrus-producing countries in North and South America, where it was first detected in Brazil in 2004 (Coletta-Filho *et al.*, 2004); then in the United States in Florida in 2005 (Halbert, 2005), in Texas in 2012 (Kunta *et al.*, 2012) and in California in 2012 (Kumagai *et al.*, 2013); in Mexico in 2009 (Trujillo-Arriaga, 2010); and in Argentina in 2012 (Badaracco *et al.*, 2017). In these countries, the most prevalent 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 irregular fruit maturation, early fruit drop, yield loss and the eventual death of the tree, as there are no resistant citrus varieties (Ramadugu *et al.*, 2016) and no commercially available cure for the disease. 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, despite the benefits, participation in AWM programs in HLB-affected areas has been irregular (Bassanezi *et al.*, 2020; Singerman and Rogers, 2020).

The collective action problem associated with AWM poses a significant challenge to HLB management, particularly in the case of area-wide insecticide treatments against the insect vector. Vector control is key to disease management because HLB epidemics are driven by bacteriliferous ACP that migrate into citrus groves (Gasparoto *et al.*, 2018). 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 $3.389 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 in the counties of Los Angeles, Orange, Riverside and San

Bernardino (CPDPP, 2021). No HLB-positive trees have been detected in commercial citrus groves to date.

Around 80% of the commercial citrus acreage in California is located in the San Joaquin Valley, in the counties of Fresno, Kern, Madera and Tulare (USDA-NASS, 2019). These counties have had very few ACP detections in recent years, so ACP is not considered to be established and citrus growers are still able to eradicate ACP populations when they are detected (Grafton-Cardwell, 2020). If an ACP is detected on a trap, citrus growers conduct locally coordinated treatments within 800 m of the find to eradicate the ACP population in that area. If ACP are found on traps repeatedly in nearby 800 m treatment areas, growers work together to simultaneously treat larger areas, in what are called “locally coordinated treatments” (UC ANR, 2019). Participation in locally coordinated treatments has been consistently high, but the routine AWM program for ACP used in Southern California has not been implemented in the San Joaquin Valley yet, so this region will not be the focus of this study.

The remaining 20% of the citrus acreage in California is distributed between the southern counties (Imperial, Riverside, San Bernardino and San Diego) and some of the coastal counties (Monterey, Santa Barbara, San Luis Obispo and Ventura). In Southern California (Imperial, Riverside, San Bernardino, San Diego, Santa Barbara and Ventura), where the ACP is established (Figure 3.1), citrus growers conduct routine AWM treatments. In general, there are two recommended insecticide treatments for ACP, one in the late summer or fall (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).

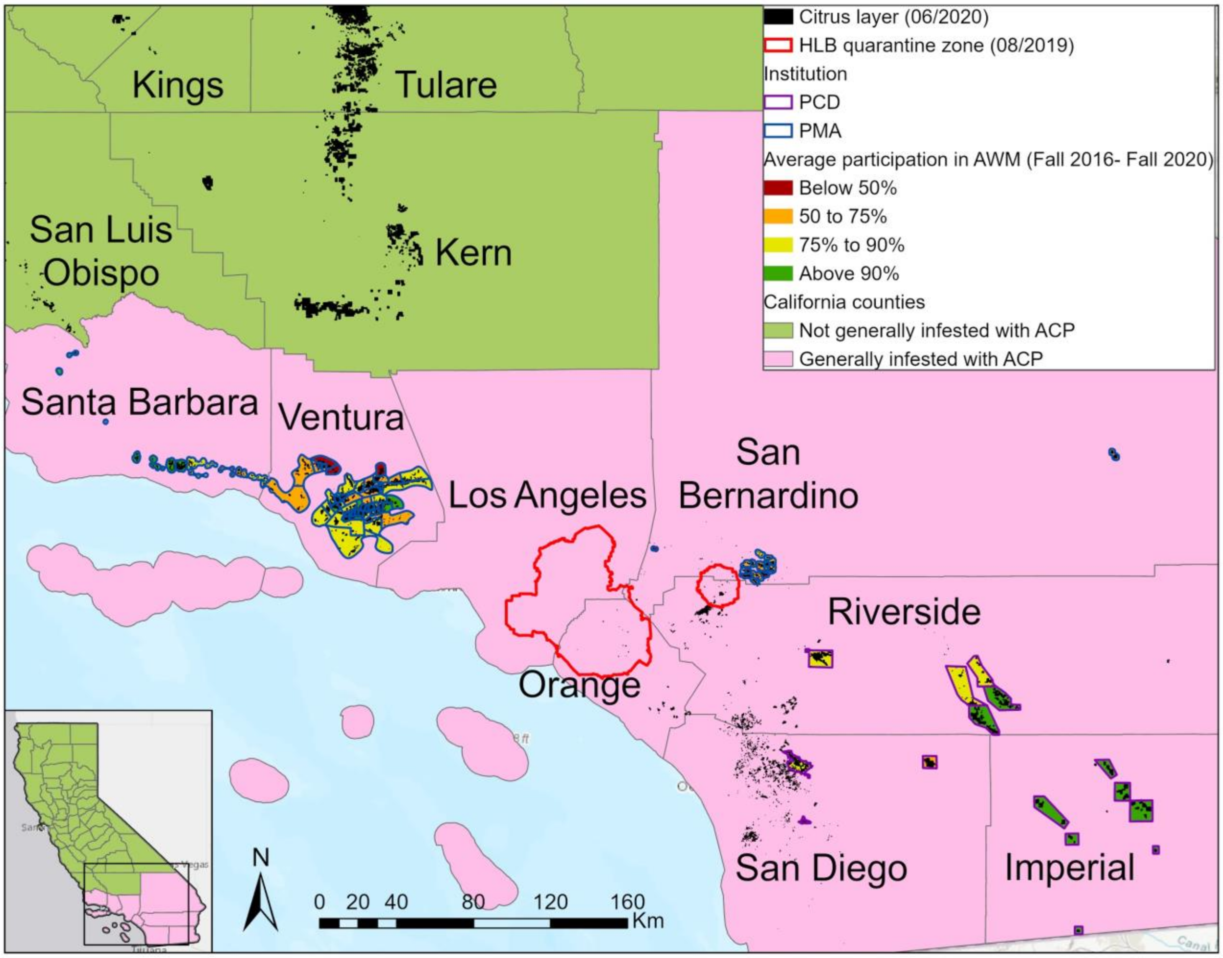


Figure 3.1: Geographical location of Psyllid Management Areas (PMAs) and Pest Control Districts (PCDs) for area-wide management (AWM) of the Asian citrus psyllid (ACP) in Southern California. The outline of PMAs is shown in blue and the outline of PCDs is shown in purple. Each PMA and PCD has been filled 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).

To overcome the collective action problem associated with AWM and to coordinate insecticide treatments for ACP, California citrus growers have adopted two distinct institutional approaches: Psyllid Management Areas (PMAs) and Pest Control Districts (PCDs) (Table 3.1).

Table 3.1: 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[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 Valley)	Formed in 1946 for California red scale control[3]	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 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 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[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.)

PMAs are voluntary groups of approximately 20 neighboring growers who 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, the growers are contacted directly by the grower liaisons. Grower liaisons are individuals with years of experience in the citrus industry as consultants, who were hired by the 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 are relying on the PMA structure 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). Within a county, PCDs are established by the majority of the growers (≥51% by area) in the proposed district, 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 isn't paid within a certain time, the County has the authority to sell that property to recoup the cost of the treatment (FAC, 1988). For citrus, PCDs currently exist in areas of Fresno, Imperial, Kern, Riverside, San Diego and Tulare; some of them already existed for other citrus pests before ACP and HLB were detected in California (Table 3.1). The PCDs in Southern California are responsible for indicating the timing of the area-wide ACP treatments in conjunction with the grower liaisons. PCDs are typically funded by assessments to its grower members on a per acre basis, and some of the PCDs (Coachella, Hemet and San Diego) incentivize coordination by providing a complete or partial reimbursement of the assessment to growers if they show proof of having complied with the AWM treatment within the recommended window.

In addition, to increase the effectiveness of the coordinated treatments and to provide an incentive for growers to participate, when at least 90% of the commercial citrus acreage in a management unit is treated within the designated window, the California Department of Food and Agriculture (CDFA) may apply buffer insecticide treatments in residential areas within 250 m of the treated commercial area to suppress ACP populations, if these areas are considered to be generally infested with ACP and homeowners consent to the treatments (CDFA, 2020). This incentive, which was created as the AWM program was getting started and was adapted over time to match the evolution of the epidemic, was the main motivation to track participation in AWM units throughout Southern California, leading to a unique record of participation in 93 different AWM units over nine seasons.

As the HLB epidemic progresses in Southern California, the main objectives of this study were to assess the citrus stakeholders' perception of the collective action problem associated with AWM and to quantify the impact of 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 provides context about the individual perceptions of

AWM as a collective action problem, and the historic record of the group-level participation in AWM from 93 management units in Southern California referred to above. Combining these two sources of information, we disentangle the interactions between individual perceptions, group-level determinants and institutional approaches that may impact collective action in the AWM of ACP in California, with the potential to also be relevant for other invasive plant pests and diseases.

MATERIALS AND METHODS

Individual perceptions of collective action in area-wide management

Survey design

The survey to assess the citrus stakeholders' perception of AWM program was designed by the researchers as part of a broader study to assess the citrus stakeholders' propensity to adopt HLB management practices in California (Garcia-Figuera *et al.*, 2021a). The questionnaire is provided as the Supplementary text 3.1.

The first six questions referred to the participants' social and economic background, and were based on available data (USDA-NASS, 2019) or previous similar studies (Mankad *et al.*, 2019; Milne *et al.*, 2018; Singerman *et al.*, 2017; Stallman and James, 2015). For these questions, participants were asked to select 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, participants were asked to indicate whether they grew citrus *conventionally*, *organically* or *both*. Finally, they were asked to indicate what percentage of their income came from citrus: *0-25%*, *26-50%*, *51-75%* and *76-100%*.

Focusing on AWM, to assess the citrus stakeholders' perception of their group efficacy (Lubeck *et al.*, 2019; Niemiec *et al.*, 2016) 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, when citrus stakeholders in California were asked "to rate the effectiveness of area-wide control of ACP", choosing between *not effective*, *little effect*, *moderate control* and *excellent control* (Milne *et al.*, 2018).

To gain insight into the citrus stakeholders' perception of the main barriers to AWM, and to determine if they were perceiving 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 the 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 part*icipate, followed by *I prefer to spray on my own timing* (Singerman *et al.*, 2017).

To measure the citrus stakeholders' confidence that others around them were contributing to the 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) and collective insect pest management (Stallman and James, 2017). We specifically asked this question after asking about the main barrier to AWM to prevent bias in the responses to the question about barriers that could potentially arise once participants were asked about their neighbors.

Finally, to contextualize the three questions within the broader HLB control program in California, we asked participants about 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); their self-reported intention to stay informed and communicate with the grower liaisons; and their self-reported intention to communicate with neighbors. These questions were also assessed on a 5-point scale of *very unlikely*, *unlikely*, *maybe*, *likely* and *very likely.* We were interested in assessing the relationship between perceived vulnerability to HLB and perceived efficacy of AWM; and also, to determine if vulnerability was related to trust in neighbors. Regarding the intention to stay informed and communicate with the grower liaisons, our expectation was that it 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). 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), we expected trust in neighbors to be positively correlated with the intention to communicate with neighbors.

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 conjunction 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 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 survey was introduced to the 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.

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 101 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 3.2.

Table 3.2: Socio-economic characteristics of the survey respondents who indicated that they had citrus groves in Southern California (n = 101).

Survey item	Responses	Percentage of total
Role in citrus production		
Grove Owner	40	40%
Ranch Manager	17	17%
PCA	19	19%
PCO	2	2%
Other	18	18%
NA	5	5%
Farm size		
< 5 acres	23	23%
5 – 25 acres	19	19%
26 – 100 acres	11	11%

101 – 500 acres	14	14%
> 500 acres	29	29%
NA	5	5%
Age		
<35 years	12	12%
35 - 50 years	14	14%
51 – 65 years	39	39%
> 65 years	36	36%
Management system		
Conventional	61	60%
Organic	13	13%
Both	24	24%
NA	3	3%
Income from citrus		
< 25%	40	40%
26 - 50%	13	13%
51 - 75%	18	18%
76 - 100%	24	24%
NA	6	6%

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

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 (54%), followed by Riverside (14%), Santa Barbara and Ventura (7%), Riverside and San Diego (5%), Santa Barbara (4%), Imperial (3%) 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). The total citrus harvested 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 (40%), PCAs (19%) or ranch managers (17%). Although 18% self-identified as *other*, we did not detect any strong evidence of differences in the distribution of responses to any of the questions in the survey among different types of stakeholders ($P \geq 0.073$ in a Kruskal-Wallis rank test), 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; USDA-NASS, 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 40% of the sample, compared with participants who depended on citrus for their livelihood (24%).

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

Data collection

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 calculated as the percentage of the total citrus acreage within each management unit that was treated within the recommended window, and they 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 93 active AWM units in Southern California: 16 operating as part of a PCD and 78 operating as PMAs. 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, so in the records, 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 all 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 (Supplementary Figure 3.1).

Theoretical framework

A regression model was used to quantify the impact of group-level determinants on participation in AWM. The dependent variable was the level of participation in AWM, measured as the percentage of the citrus acreage within each management unit (PCD or PMA) treated within the designated treatment window. Independent variables were chosen based on recent studies related to collective action and invasive species management (Graham *et al.*, 2019; Lubeck *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 (see Table 3.3) were considered for inclusion in the model selection/fitting exercise:

1. *Institutional approach*: PMA (baseline) or PCD. Because of the mandatory nature of PCDs and the requirement for PCD assessments to be collected on a per-acre basis, we hypothesized that PCDs would have higher participation levels than PMAs, all other factors being equal, as PMAs are voluntary and require a lower degree of commitment. Preliminary analysis supported the inclusion of this variable, as 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 ($P=0.99$).
2. *Group Size* of each PMA or PCD. Based on the collective action literature, we hypothesized that management units with fewer members would have higher participation levels, as there would be fewer people who would need to agree to treat in coordination, and the transaction costs of coordination would be lower (Ostrom, 2009). Our hypothesis was supported by preliminary analyses, as there was a significant negative correlation between the number of pesticide use permits and participation ($\rho=-0.28$, $P<2.2\text{E-}16$). Therefore, to include the group size in our regression model, we calculated 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 Citrus Research Board (CRB). This database (hereafter referred to as the *citrus layer*) contains

information about the acreage, ownership, pesticide use permit number, commodity and other relevant information about properties with more than 25 citrus trees in the state of California, and it is regularly updated. We obtained access to the version of this database corresponding to June of 2020 (Rick Dunn, personal communication) and the outlines of each AWM unit in the state of California (Rick Dunn and Robert Johnson, pers. com.), and we used the software ArcGIS Pro (ESRI, Redlands, CA, U. S. A.) to calculate the number of different PURs within each management unit, 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).

3. *Size of the resource system*, *i.e.*, total citrus acreage under each management unit. From an ecological perspective, the bigger the PMA or PCD, the more effective the coordinated treatments against ACP will be, as the insect will not be able to disperse to nearby untreated groves (Flores-Sánchez *et al.*, 2017; Rogers *et al.*, 2010). However, as the citrus acreage under a management unit 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). To test if the total size of the unit by itself had a negative effect on participation, after controlling for the size of the group, we calculated the total size of each PMA and PCD based on the information in the CRB citrus layer. Using the "Dissolve" tool from the software ArcGIS Pro, we aggregated all of the citrus properties in each PMA/PCD and calculated the mean, median, standard deviation and sum of the grove acres. Our calculation of the 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).

4. *Size of citrus groves.* We hypothesized that PMAs or PCDs with bigger groves would have higher participation levels, because bigger operations may have more resources to treat and their owners may be more invested in citrus production. This hypothesis was supported by preliminary analysis that indicated that there was a significant positive correlation between the average size of citrus groves and participation (ρ=0.27, *P*≤2.2E-16). The average grove size in each management unit was calculated using the software ArcGIS Pro, as previously indicated.
5. *Heterogeneity in grove size*. Because heterogeneity has been found to deter collective action for pest management (Stallman and James, 2017), we hypothesized 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. The standard deviation of the size of citrus groves in each management unit was calculated using ArcGIS Pro as previously indicated. In addition, to test if the effect of heterogeneity on participation was conditioned on the average size of citrus groves, we included an interaction term between the mean and standard deviation of the size of citrus groves.
6. *Season of Treatment*: fall (baseline) or winter. Because ACP populations in California tend to peak at the end of the summer or the beginning of fall due to the availability of citrus flush (*i.e.*, young leaf growth), entomologists have emphasized the importance of fall treatments to reduce ACP populations (Grafton-Cardwell, 2020). Therefore, we hypothesized that fall treatments would have higher participation than winter treatments, which are mostly preventive and aimed at targeting ACP adults that may have survived through the coldest months of the year, before the spring flush.

7. *Age of Program.* Our hypothesis was that we would not see a systematic change in participation with time, but 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.

To measure the benefits that citrus stakeholders may obtain from AWM, we considered the inclusion in the regression model of an eighth independent variable that measured the proximity of the management unit to the closest HLB-positive tree, which provided a proxy for vulnerability; and an ninth independent variable that measured the percentage of the land within each unit dedicated to citrus, which provided a proxy for the importance of citrus in each PMA/PCD. Perceived vulnerability was recently found to be a key factor in the propensity to adopt other HLB management practices (Garcia-Figuera *et al.*, 2021a), so we hypothesized that it could be an important factor in the decision to participate in AWM. Similarly, in successful cases of self-organization for CPR management, users tended to be dependent on the resource system for their livelihood (Ostrom, 2009). Therefore, our initial hypotheses were that, all other factors being equal, management units that were closer to HLB would have higher AWM participation levels; and units that had a higher percentage of the land dedicated to citrus would also have higher participation. However, preliminary analysis did not give support to these hypotheses, as there was a significant positive correlation between participation and distance from HLB ($\rho=0.38$, $P<2.2E-16$) and a significant negative correlation between participation and percentage of the land within each unit dedicated to citrus ($\rho=-0.22$, $P<1.9E-10$). The first correlation may be an artifact of the dataset, because two of the PCDs with the highest participation levels (Imperial County PCD and Coachella Valley PCD) are among the furthest from HLB-positive trees in Southern California. Therefore, we decided not to include distance from HLB as an independent variable to estimate participation. Similarly, because PMAs and PCDs were specifically designed to facilitate coordination of citrus pest treatments, most of the land within these areas is actually dedicated to citrus production, according to public databases (Department of Water Resources, 2020). Thus, we believe that the inclusion of this variable may be irrelevant, or even misleading. Further support for the non-inclusion of these two variables could be inferred from the survey, where perceived vulnerability to HLB and income dependency on citrus were not found to impact the perception of AWM by citrus stakeholders, as explained below.

Table 3.3: Measurement and expected sign of the independent variables in the regression model

Independent variable	Type of variable	Expected sign
Institutional approach	Categorical (PMA/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/Winter)	Negative
Age of program	Numeric (1-9)	?

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) and 112 observations at 1 (60 PCDs and 101 PMAs). Given these characteristics, we chose to use a zero-and-one-inflated beta (zoib) regression model (Liu and Kong, 2015). This model is based on the assumption 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

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

where p_i represents the probability Pr(y_i=0), q_i represents the conditional probability Pr(y_i=1 | y_i≠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 (Supplementary Table 3.1, Supplementary Table 3.2).

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.

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 calculated using the R package "dplyr" (Wickham *et al.*, 2021) and base R. Correlations between ordered categorical variables from the survey were tested using Spearman's rank correlation test, and correlations between numeric independent variables in the regression model were tested using Pearson's correlation test. Regression models were constructed using the R package "zoib" (Liu and Kong, 2015). Plots were generated with the R package "ggplot2" (Wickham, 2016). All the code used in this study will be posted in a repository at the following URL after publication of this study: https://github.com/nmcr01?tab=repositories.

RESULTS

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

Through a survey answered by 101 participants in Southern California, we obtained an assessment of the citrus stakeholders' perception of the AWM program for ACP four years after its implementation. To assess the participants' trust in the efficacy of AWM, 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 majority (88%) thought that it was *likely* or *very likely*, revealing a robust consensus about the efficacy of AWM (Figure 3.3). Participants with different socio-economic backgrounds did not provide significantly different answers to this question, and the high level of trust in the relative efficacy of AWM was consistent across different counties. Therefore, despite the differences in participation that will be explored in the next section, there seems to be widespread agreement about the benefits of coordinating insecticide treatments against ACP to prevent HLB spread. Interestingly, there was no correlation between the participants' perceived vulnerability to HLB and their trust in the efficacy of AWM, but 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=0.048, Supplementary Figure 3.2). Therefore, engagement with the CPDPP may promote confidence in the efficacy of AWM.

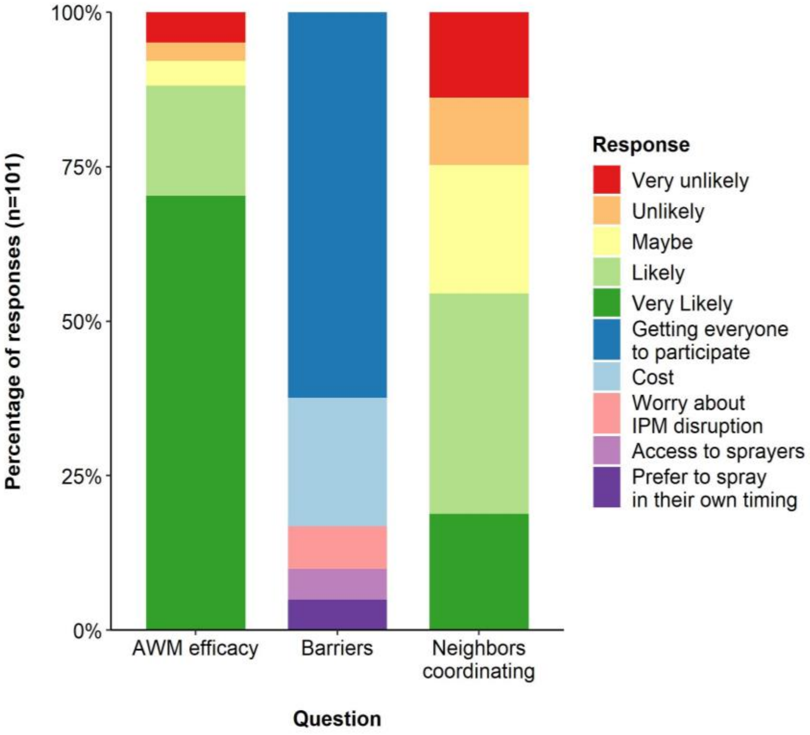


Figure 3.3: Perception of area-wide management by citrus stakeholders in Southern California. The bars represent the percentage of participants who chose each response. Responses have been color-coded according to the legend on the right. *AWM efficacy* corresponds to the question "How likely do you think it is that coordinated treatments against ACP would slow down the spread of HLB more than uncoordinated treatments?". *Barriers* corresponds to the question "What do you think is the main barrier to area-wide management of ACP in your area?". *Neighbors coordinating* corresponds to the question "How likely do you think it is that your neighbors will apply insecticides for ACP within recommended treatment windows?".

To provide historic context to our survey, the answers to the question about the participants' trust in the efficacy of AWM were compared with a similar question that had been asked in an equivalent survey in 2015, as 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". Most participants from Southern California thought that it provided *moderate control* (65%), some thought that it provided *excellent control* (17%), and some (18%) considered it to be of *little effect* or *not effective* (Milne *et al.*, 2018, raw data). In 2015, there was a significant association between the location of the participants' grove and their perception of the efficacy of AWM, as growers in the San Joaquin Valley thought spraying insecticides for ACP was more effective than growers from Imperial, Riverside or San Bernardino (Milne *et al.*, 2018). Although responses from the Valley are not shown in this study, we did not detect any differences in trust in the efficacy of AWM between the Valley and Southern California, providing evidence that four years into the HLB epidemic, there is widespread agreement about the benefits of AWM to delay HLB spread.

Survey participants were also asked to identify what the main barrier to AWM was in their area. In 2019, the majority thought that it was *getting everyone to participate* (62%), about a fifth thought that it was *cost* (21%), and a few thought that it was *worry about IPM disruption* (7%), *access to sprayers* (5%) or *preference to spray in their own timing* (5%) (Figure 3.3). 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. *Access to sprayers* emerged as a concern in San Bernardino and San

Diego, in line with comments from the grower liaisons that there is a shortage of spray equipment in those counties.

As the AWM program was getting started in 2015, the majority of respondents from Southern California indicated that *participation* was among their biggest concerns about PMAs (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, raw data). Comparing these answers with the answers we obtained in 2019, it is clear that 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. Interestingly, when *pesticide resistance*, *IPM program* and *options for organic* were grouped under *worry about IPM disruption* in 2019, this barrier was selected by 7% of participants, compared with 50% of participants choosing it as one of the barriers in 2015. This may suggest that the experience acquired over four years of AWM implementation in Southern California, where only two coordinated sprays are recommended over the entire region at the moment, has probably lowered concerns about the negative effects of repeated insecticide sprays on citrus IPM programs.

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 (55%) thought that it was *likely* or *very likely*; about a fifth (21%) chose *maybe*; and a quarter (25%) thought that it was *unlikely* or *very unlikely* (Figure 3.3). 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 among citrus growers in Florida (Singerman and Useche, 2019). The 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 not robust evidence for differences among counties in terms of participants' trust in neighbors (*P*=0.085 on the Kruskal-Wallis test).

Among participants who thought that the main barrier to AWM was *getting everyone to participate*, half (50%) thought that it was *likely* or *very likely* that their neighbors would apply insecticides within designated treatment windows, while more than a quarter (28%) 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).

Finally, we detected a positive correlation between the self-reported propensity to communicate with neighbors and trust in the neighbors' ability to coordinate (ρ= 0.20, *P*=0.05, Figure A3.3), so participants who indicated that they were more likely to communicate with their neighbors also thought that it was more likely that their neighbors would coordinate. This correlation highlights the importance of communication to develop trust in others' contributions to achieve collective efforts.

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 that had 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 3.4). Other fitted models are shown on Supplementary Tables 3.1, 3.2 and 3.3.

Table 3.4: 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†	-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‡	-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†	-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†	-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
Observations	840					
DIC	1679849					
psrf	1.1					

† 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

In the selected zoib model, the signs of the coefficients of the independent variables were mostly as hypothesized (Table 3.1). Our first hypothesis was that PCDs would have higher participation than PMAs on the basis that PMAs are voluntary, while PCDs are self-imposed by local growers to mandate AWM treatments. The coefficient of the institutional approach was negative (Table 3.4), 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 has been growing over time in PCDs, while it has been declining over time in PMAs. In fact, when the model was used to predict participation based on the type of institution while fixing all other variables at their mean value, it was clear that even though PCDs started with lower participation levels, participation has followed an upward trajectory over time in this institution, while it has followed a downward trajectory in PMAs (Figure 3.4).

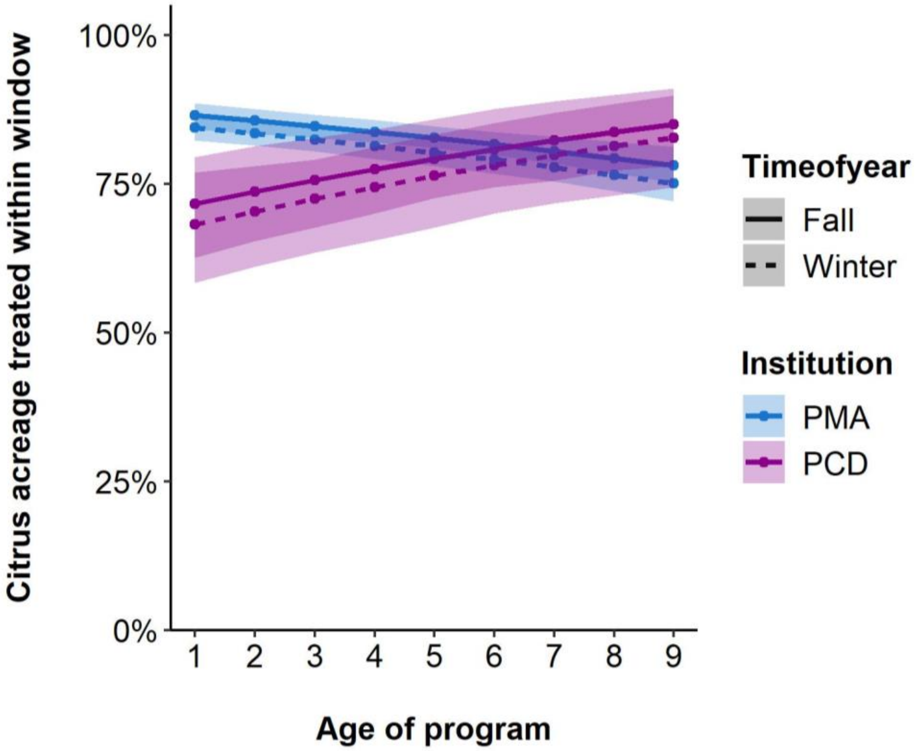


Figure 3.4: Participation levels in AWM predicted by the zoib model depending on the institutional approach (PMA/PCD), the season of treatment (Fall/Winter) and the age of the program. The dots show the mean of the predicted values in blue (PMAs) or in purple (PCDs), and the shaded areas correspond to 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.

As shown on Figure 3.4, the season when the AWM treatments are conducted was found to have an effect on participation. As hypothesized, winter treatments were found to have 0.84 [exp(-0.169)] times the odds of having higher participation than fall treatments (Table 3.4). Therefore, all other factors 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 shown to be crucial for ACP control in citrus groves in Florida (Qureshi and Stansly, 2010) and Texas (Sétamou, 2020).

In line with the collective action literature, the model estimated that the 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 holding all other variables at their mean value. Under these conditions, the model predicted that participation in a PCD would drop from 86% with 10 members to 82% with 30 members, and in a 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 total acreage, average grove size and average heterogeneity in grove size (Figure 3.5).

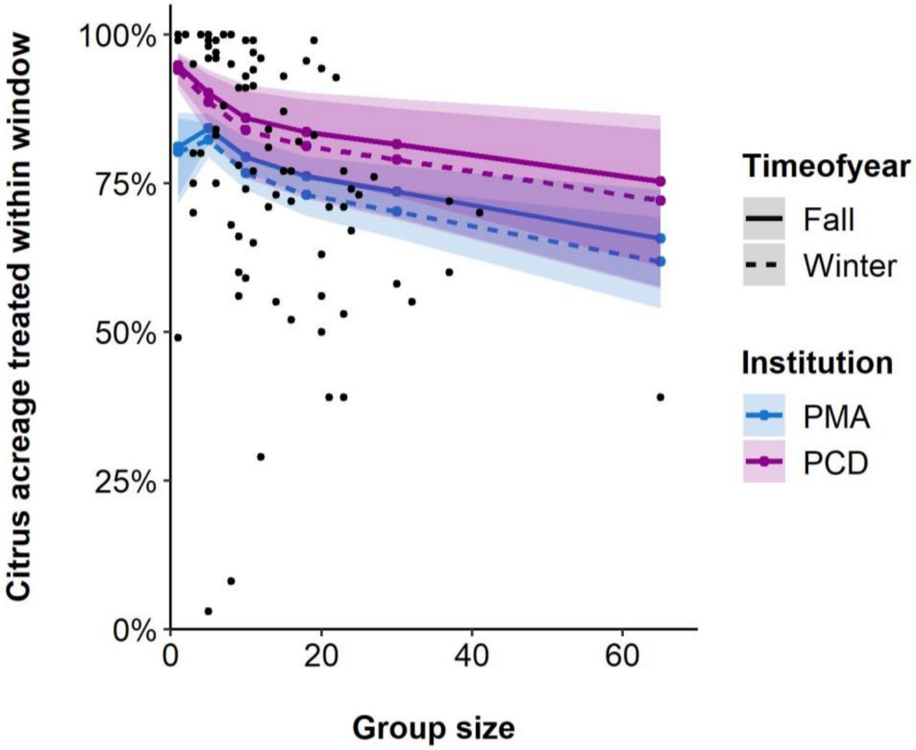


Figure 3.5: Participation levels in AWM predicted by the zoib model depending on the number of pesticide use permits. The mean of the predicted values for season number 9 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked by solid lines and predicted values 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).

Contradicting the collective action literature, 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 3.4, 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. However, we decided to keep this variable in the model because its inclusion lowered the DIC and multivariate psrf compared with the model without it (Supplementary Table 3.3), the CI for this variable did not actually comprise zero, and it allowed us to control for the total size of the unit, which is the denominator in the calculation of participation levels.

As hypothesized, the model showed that the size of the citrus groves and the heterogeneity in grove size had an impact on participation (Table 3.4). More importantly, these factors interacted, so the effect of heterogeneity on participation depended on the size of citrus groves, and the effect of the size of the groves on participation depended on the heterogeneity in grove size. As shown on Figure 3.6, when the groves were mostly small (with an average size of 2 acres), the presence of a few large groves that increased the standard deviation in size 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 if the standard deviation of the grove size was increased by the presence of a few small groves.

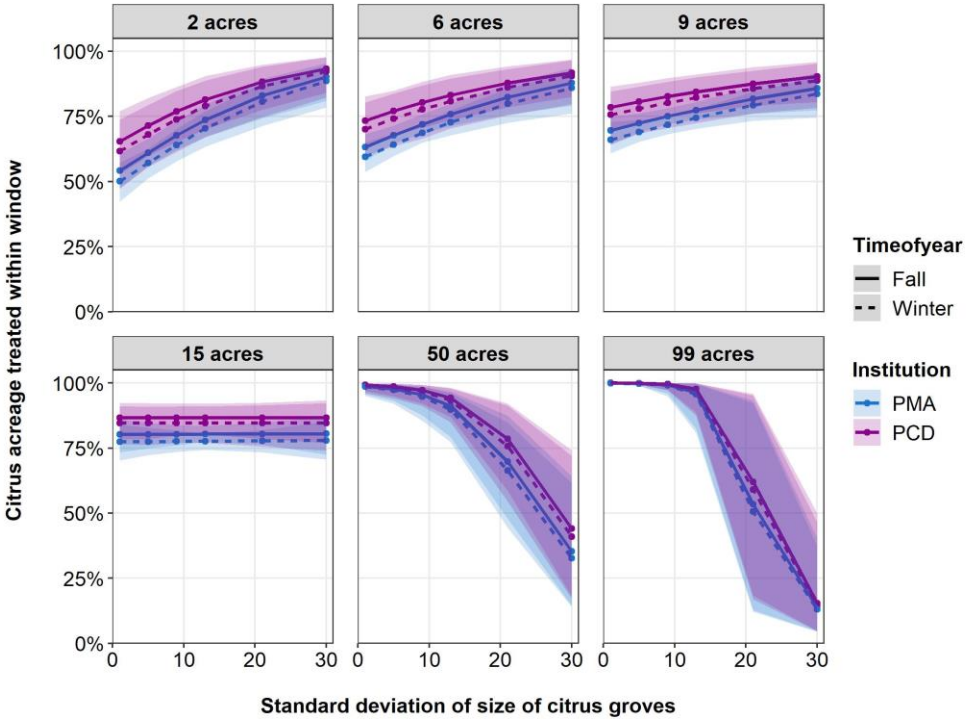


Figure 3.6: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and the heterogeneity in grove size. The mean of the predicted values for season number 9 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are linked 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. Plots corresponding to other values of the age of the program are shown in Supplementary Figures 3.4 - 3.11.

Considering that around 34% of the citrus groves in Southern California that are routinely conducting AWM treatments have less than 5 acres, heterogeneity may not have been a negative factor to date, but it could become relevant in areas predominated by big groves intermixed with a few smaller operations.

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 agreement about 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. In a recent review of collective action in invasive species management, collective responses were found to be enhanced when stakeholders acknowledged the cross-boundary nature of the problem and were aware of the benefits associated with collective action (Graham *et al.*, 2019), so citrus stakeholders may be in a good position to achieve collective action. In the context of collective weed control, awareness of cross-boundary interrelationships, beliefs about normative behaviors or expectations, 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 encourage communication between neighbors and to promote engagement with the state-wide HLB control program. 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 a 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). In our study, we detected a negative effect of heterogeneity on participation when the majority of citrus groves in the management unit were big, but survey participants with big citrus operations did not think their neighbors were *unlikely* or *very unlikely* to treat coordinately more than other categories. In fact, it was the category of small growers (less than 5 acres of citrus) which had a higher proportion of participants who mistrusted their neighbors. These small growers may come from communities with a large number of growers, and while they are the ones who come to the meetings and are engaged in the program, they may be aware that their neighbors are not well informed or connected to the program.

Our survey did not allow us to directly link individual-level responses to group-level outcomes, but we believe that it provides valuable context for a rare example in the literature of a collective effort that has been quantified over time. In Florida, which used to be the main citrus-producing state in the US, a similar AWM program was implemented for ACP and it failed to achieve collective action (Singerman and Rogers, 2020). An experimental voluntary contribution game was conducted with Florida citrus growers, showing 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. A recent review recommended to replace the voluntary character of the AWM program for ACP in Florida with a mandatory component, suggesting to implement 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 to achieve collective action. Although there are precedents of successful AWM programs for other plant pests and diseases in the state (Simmons *et al.*, 2021; Sisterson *et al.*, 2020), 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 (Bassanezi *et al.*, 2020; Graham *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, all other variables being constant, PCDs have been growing in participation over time, while participation has been declining in PMAs. 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 the 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 that influenced collective action for invasive species management (Graham *et al.*, 2019). As there are increased transaction costs associated with organizing larger groups and the probability of free-riding is higher (Graham *et al.*, 2019), we expected that participation in AWM would go down as the number of people who needed to coordinate treatments increased. In fact, this was one of the reasons why PMAs were designed based on 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 based on epidemiological criteria to comprise a sufficiently large area to achieve ACP control (Rogers, 2011), and similar epidemiological criteria were followed in Mexico (SENASICA, 2012). In our analysis, 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.

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 applications at the same time has been a limiting factor for participation in some counties. Unfavorable weather events (high winds, mud slides, wildfires) have also had a negative impact on participation, and may explain some of the 0 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. In addition, 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 interested in spending resources to take care of their citrus trees, so they have become the weakest-link in the collective action problem of AWM. 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.

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 costs and benefits 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 "comanaged" 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, and our hope is that this study will contribute to that effort.

CONCLUSIONS

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.

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SUPPLEMENTARY MATERIALS

Supplementary text 3.1: 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 coordinated insecticide treatments for ACP will slow down HLB spread more than uncoordinated treatments?

a. Very unlikely

b. Unlikely

c. Maybe

d. Likely

e. Very likely

12.What do you think is the main barrier 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?

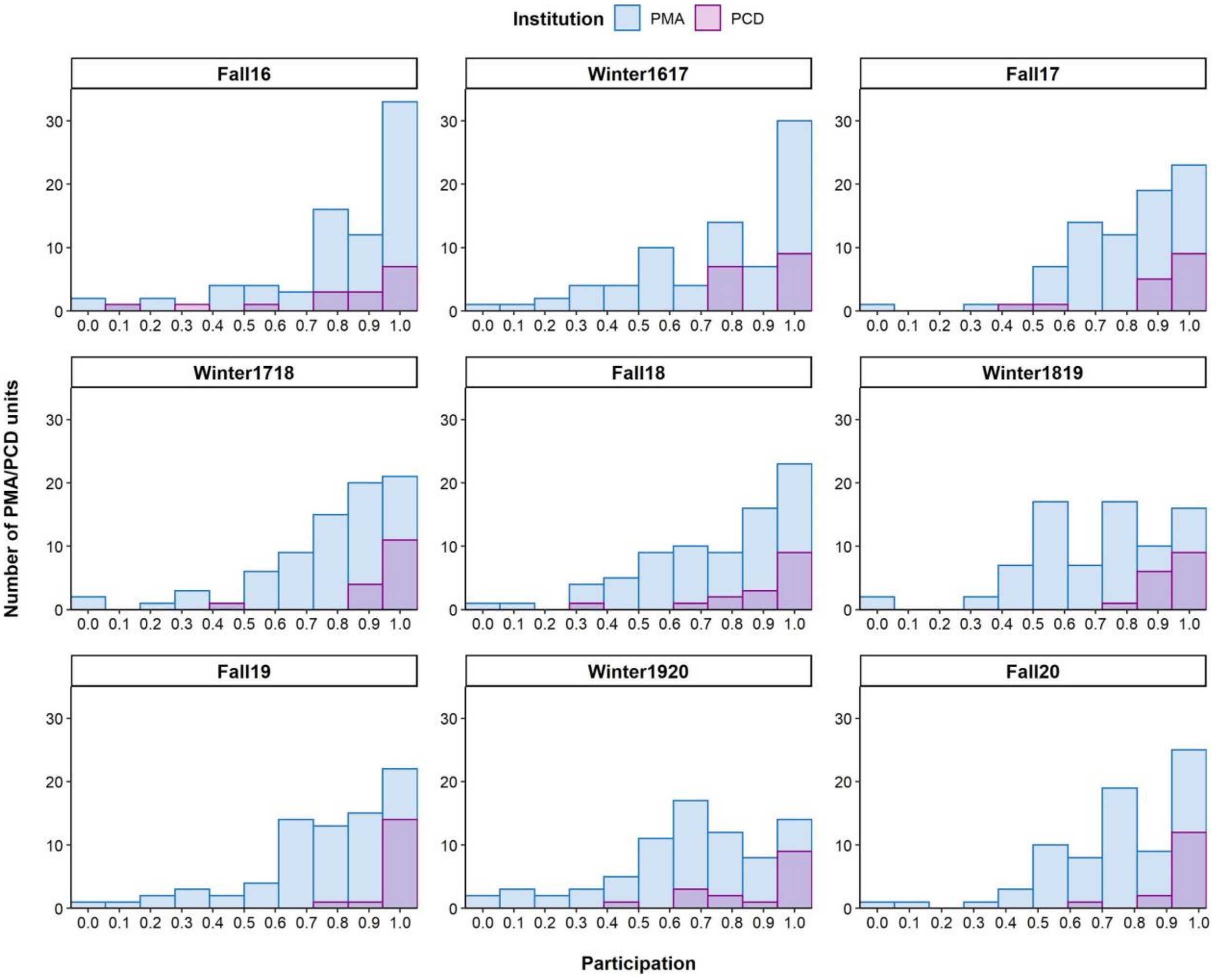
a. Very unlikely

b. Unlikely

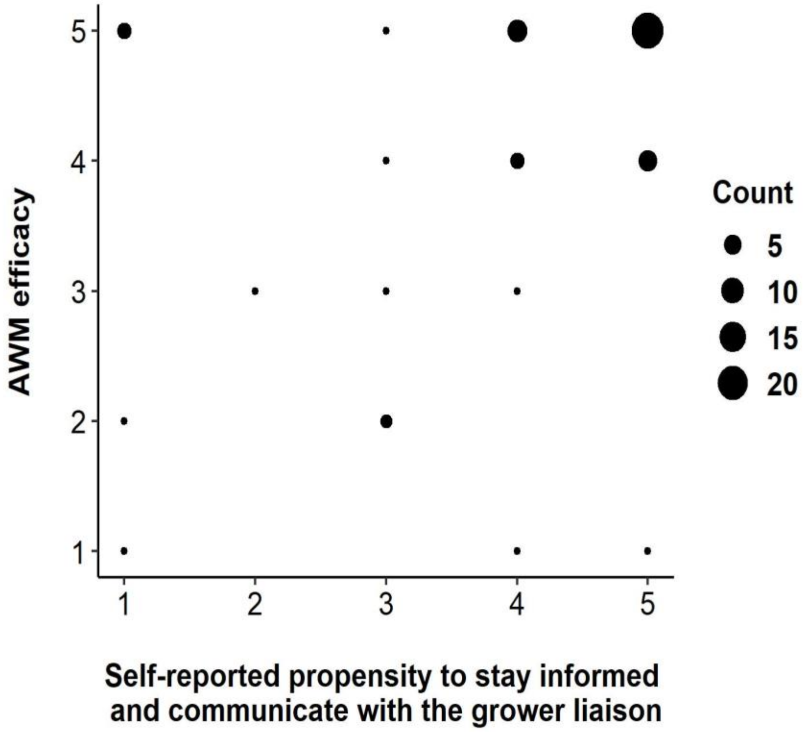
c. Maybe

d. Likely

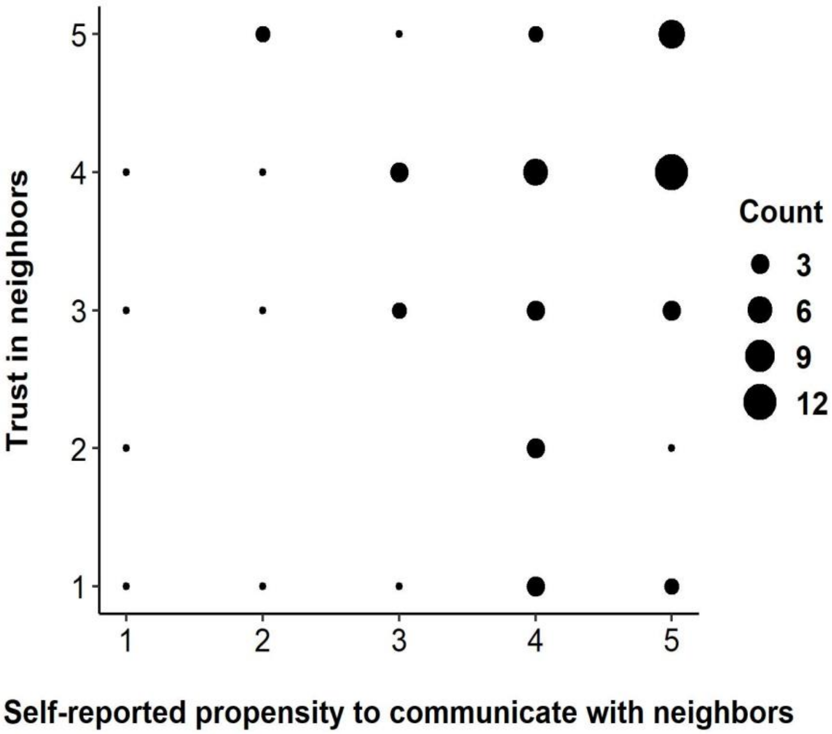
e. Very likely



Supplementary Figure 1.1: Histogram of participation levels in area-wide management in Psyllid Management Areas (blue) and Pest Control Districts (purple) over nine seasons.



Supplementary Figure 1.2: 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.



Supplementary Figure 1.3: 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.

Supplementary Table 3. 1: 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

Supplementary Table 3. 2: 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

Supplementary Table 3. 3: 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).

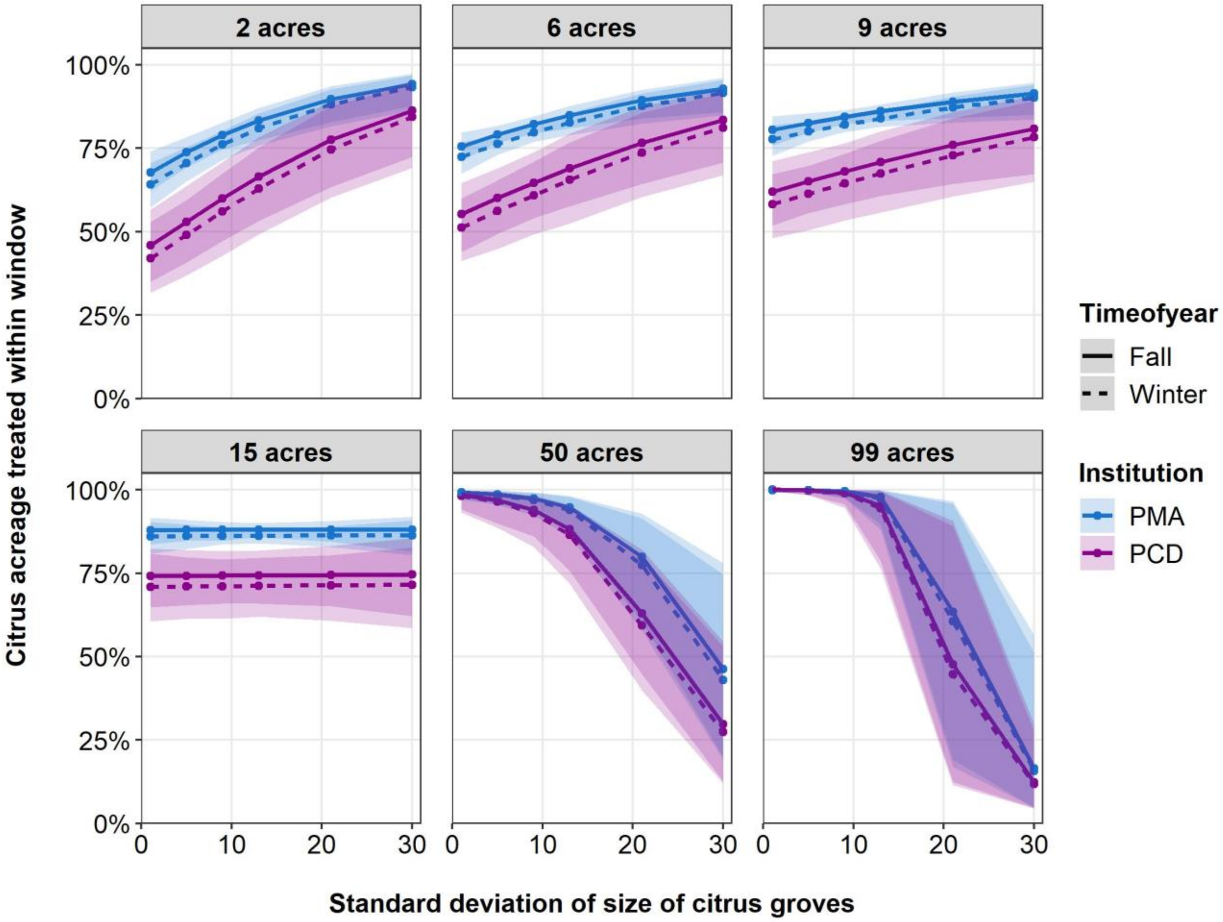
		SD28 **mean**	**SD28** **2.5%**	**SD28** **97.5%**	SD32 mean	SD32 2.5%	SD32 97.5%
logit(mean)	Institutional approach†	**-1.09**	**-1.65**	**-0.57**	-0.65	-1.17	-0.13
	Group size	**-0.01**	**-0.02**	**0.00**	-0.01	-0.01	0.00
	Size of resource system	**0.00**	**0.00**	**0.00**			
	Grove size	**0.10**	**0.06**	**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		

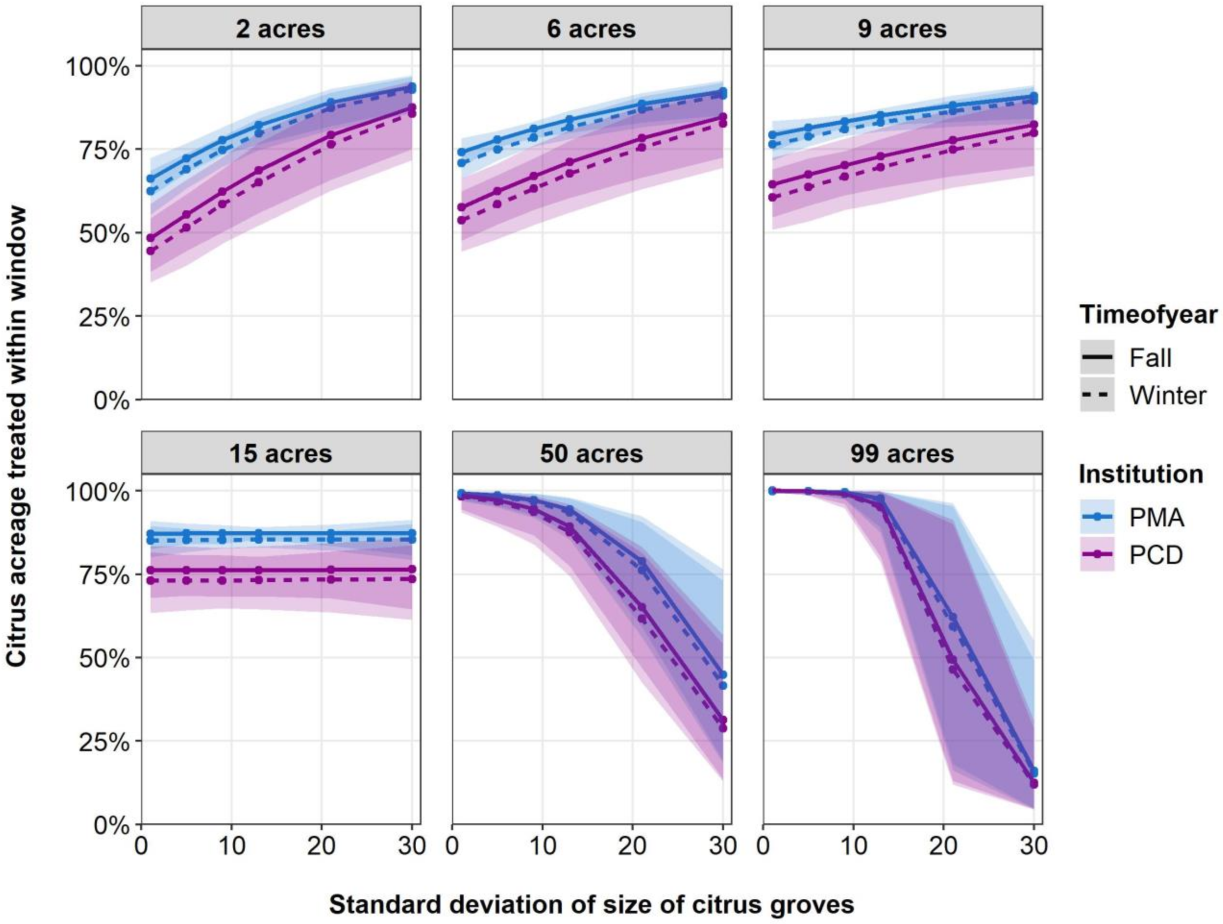
Note: deviance information criterion (DIC), potential scale reduction factor (prsf)

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

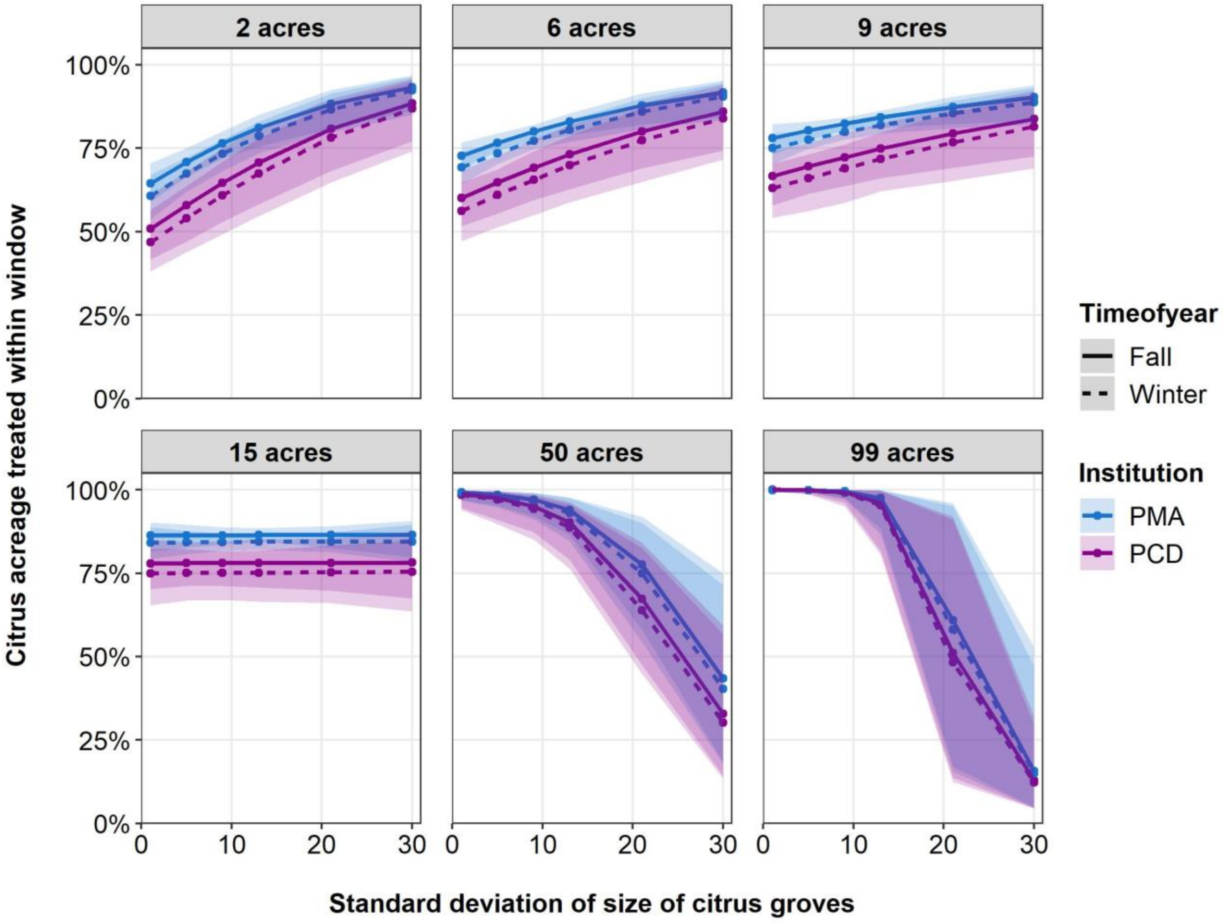
‡ Season of treatment was modeled as a factor, considering Fall as the baseline



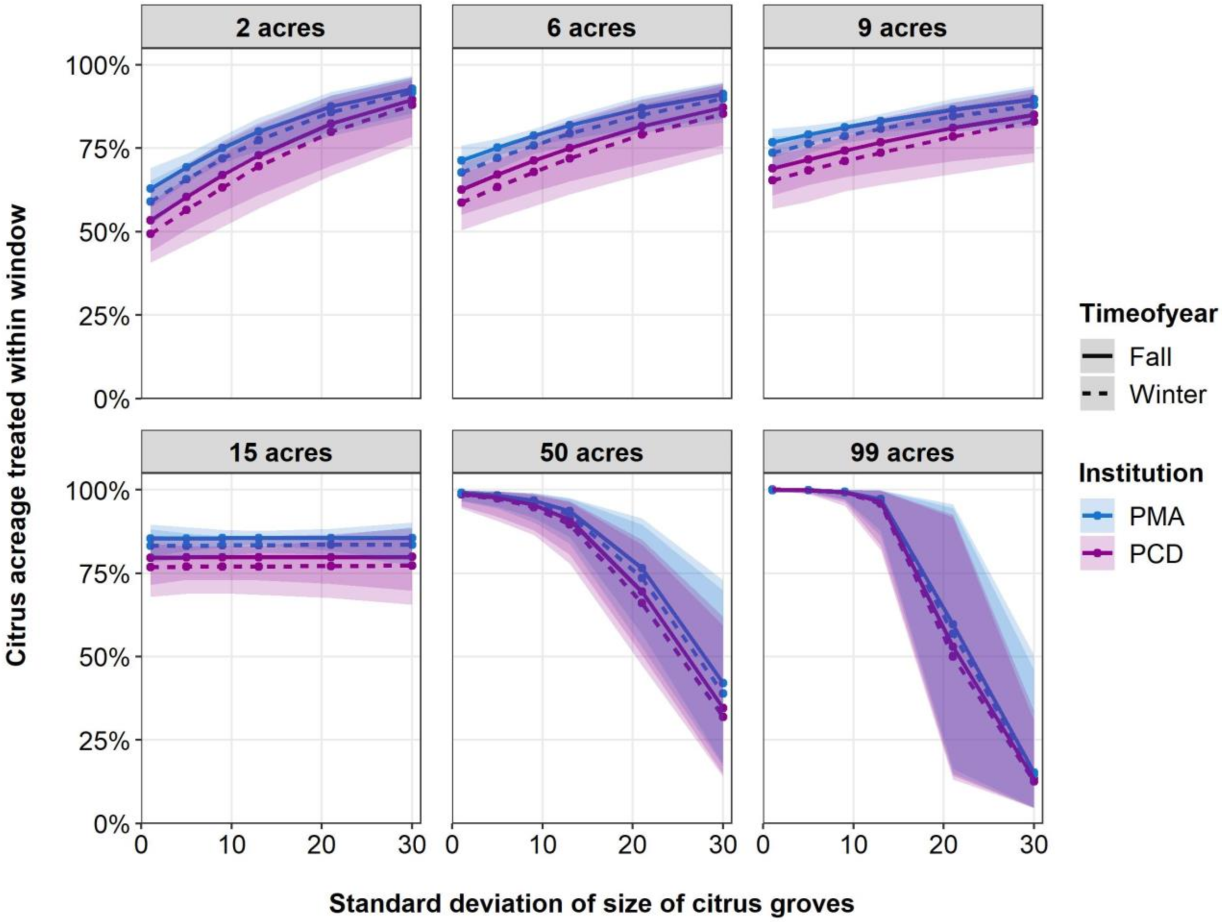
Supplementary Figure 3. 4: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 1 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are 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.



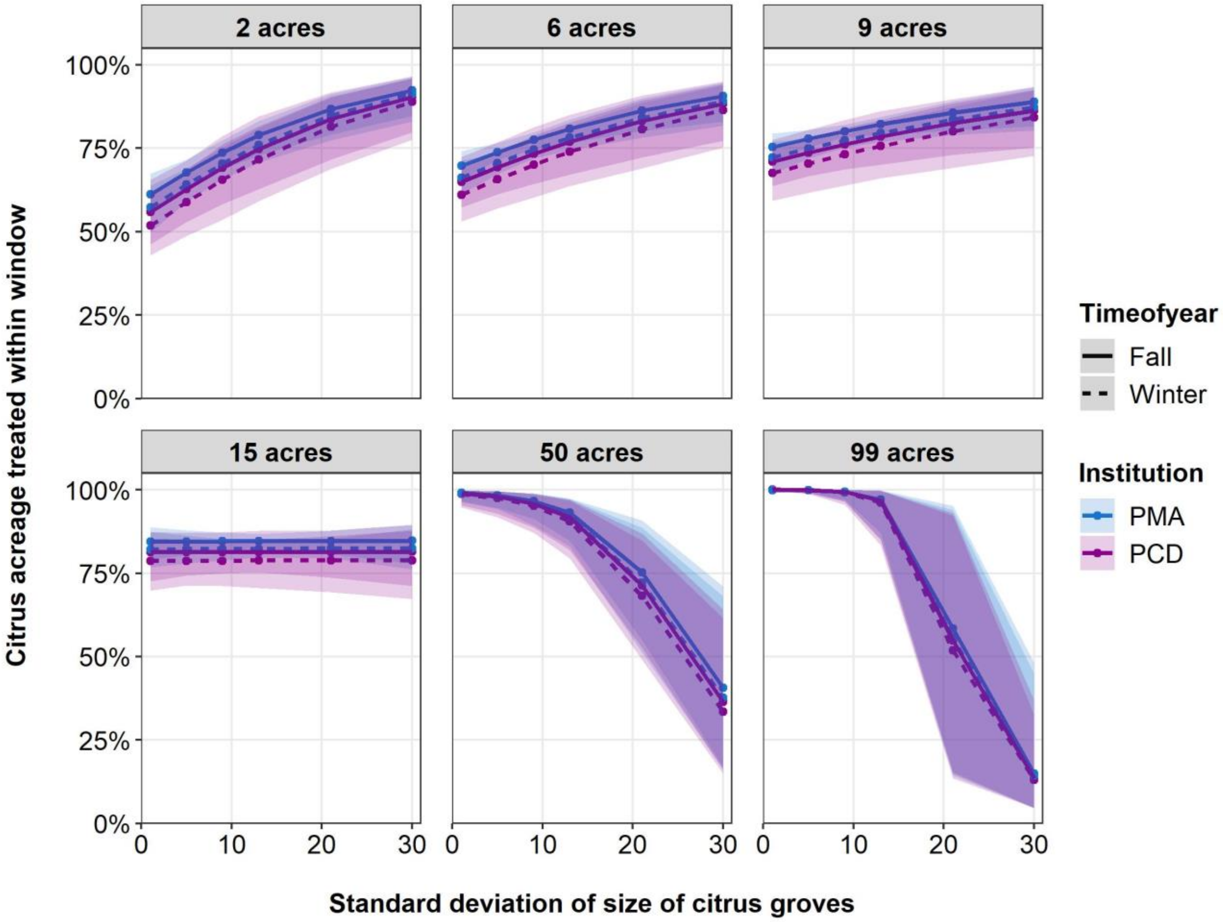
Supplementary Figure 3. 5: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 2 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are 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.



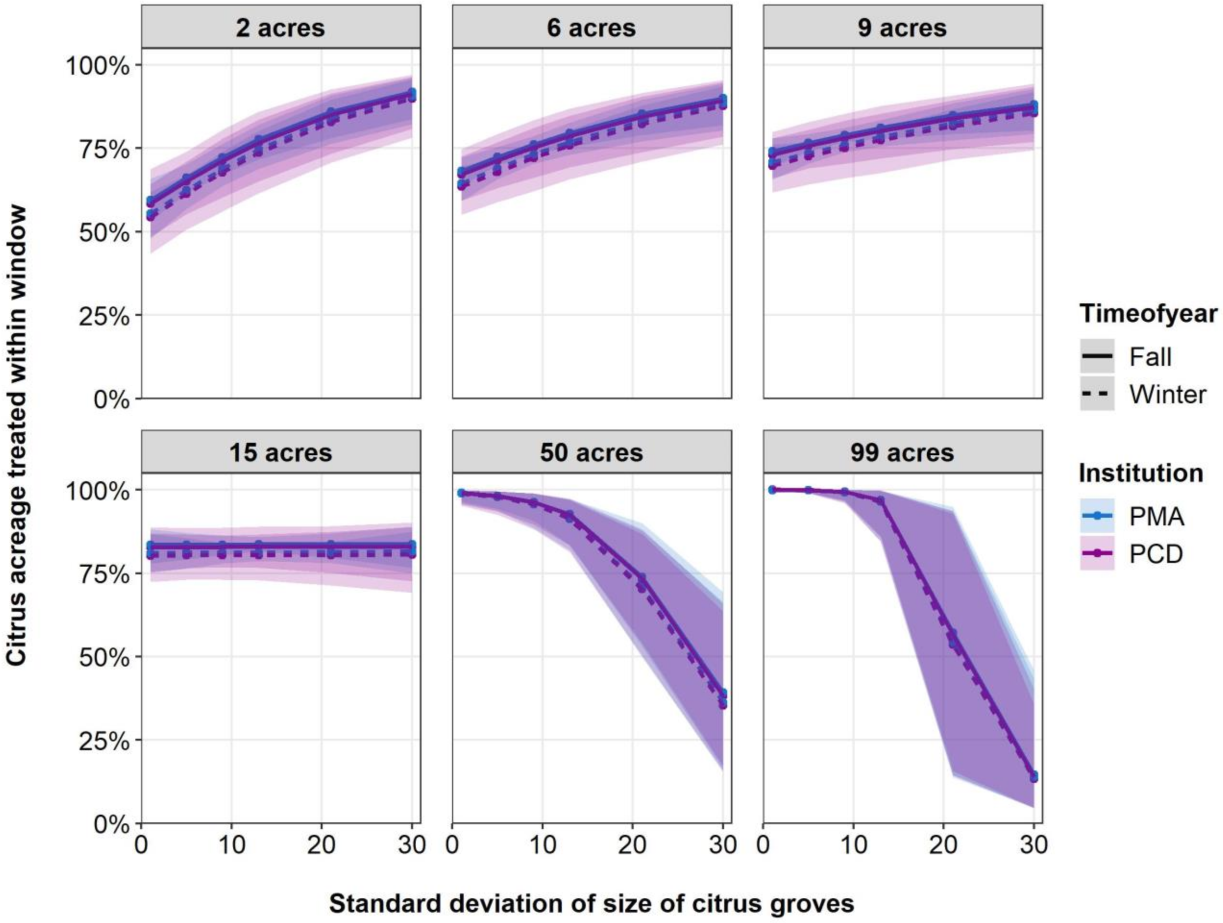
Supplementary Figure 3. 6: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 3 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are 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.



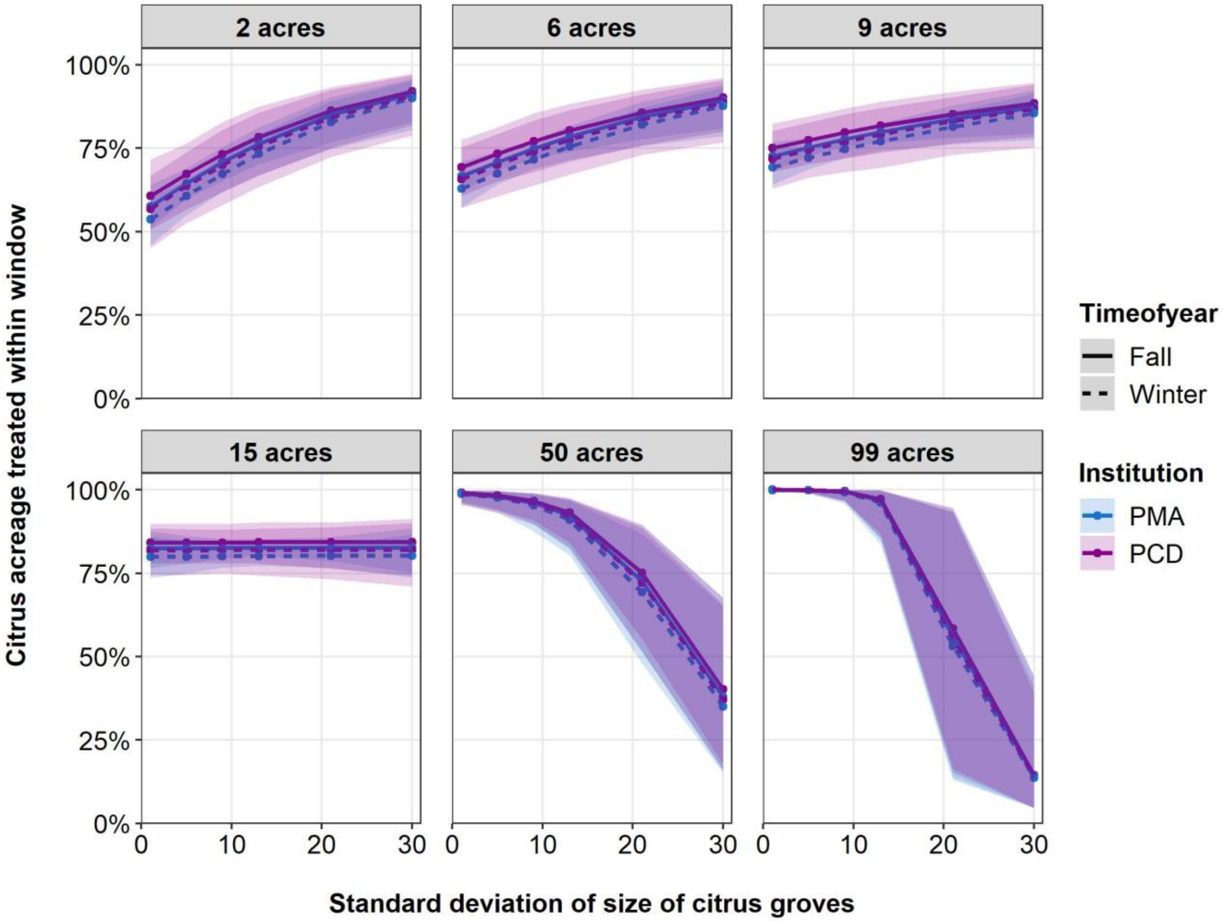
Supplementary Figure 3. 7: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 4 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are 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.



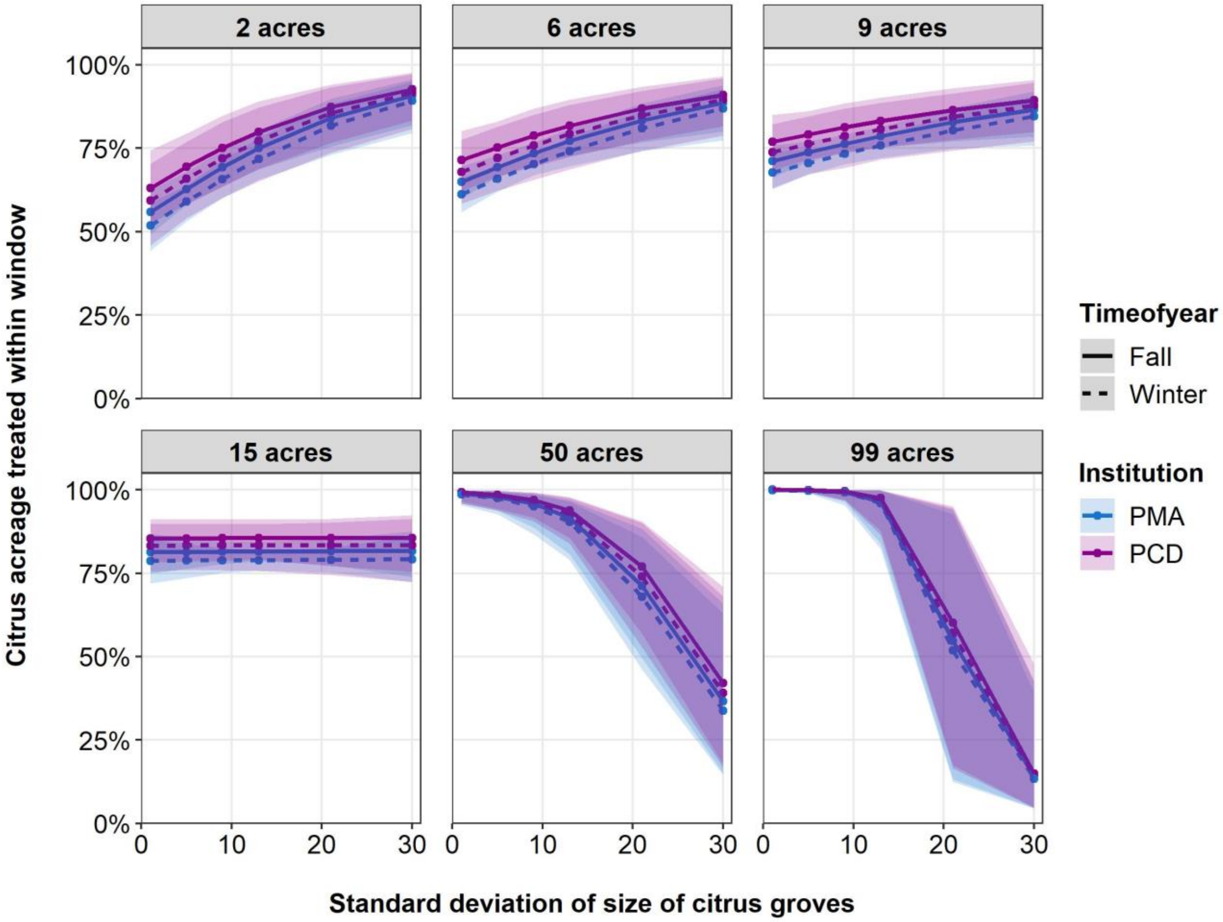
Supplementary Figure 3. 8: Participation levels in AWM predicted by the zoib model depending on the average size of the citrus groves and their heterogeneity. The mean of the predicted values for season number 5 is shown in blue (PMAs) or in purple (PCDs). Predicted values for the fall treatments are 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.



Supplementary Figure 3. 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.



Supplementary Figure 3. 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.



Supplementary Figure 3. 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 unit.