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REVIEW

Institutional approaches for plant health provision as a collective action problem

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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.

Keywords Plant health · Collective action · Public good · Area-wide management · Invasive species · Huanglongbing

1 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

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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, 2003), 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 & 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.

2 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 & 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 (Fig. 1).

HLB is difficult to eradicate because ACP is mobile and prolific, *C*Las 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 & 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 & 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 & Chancellor, 2002). Rice plants can become infectious within 1 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 & 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

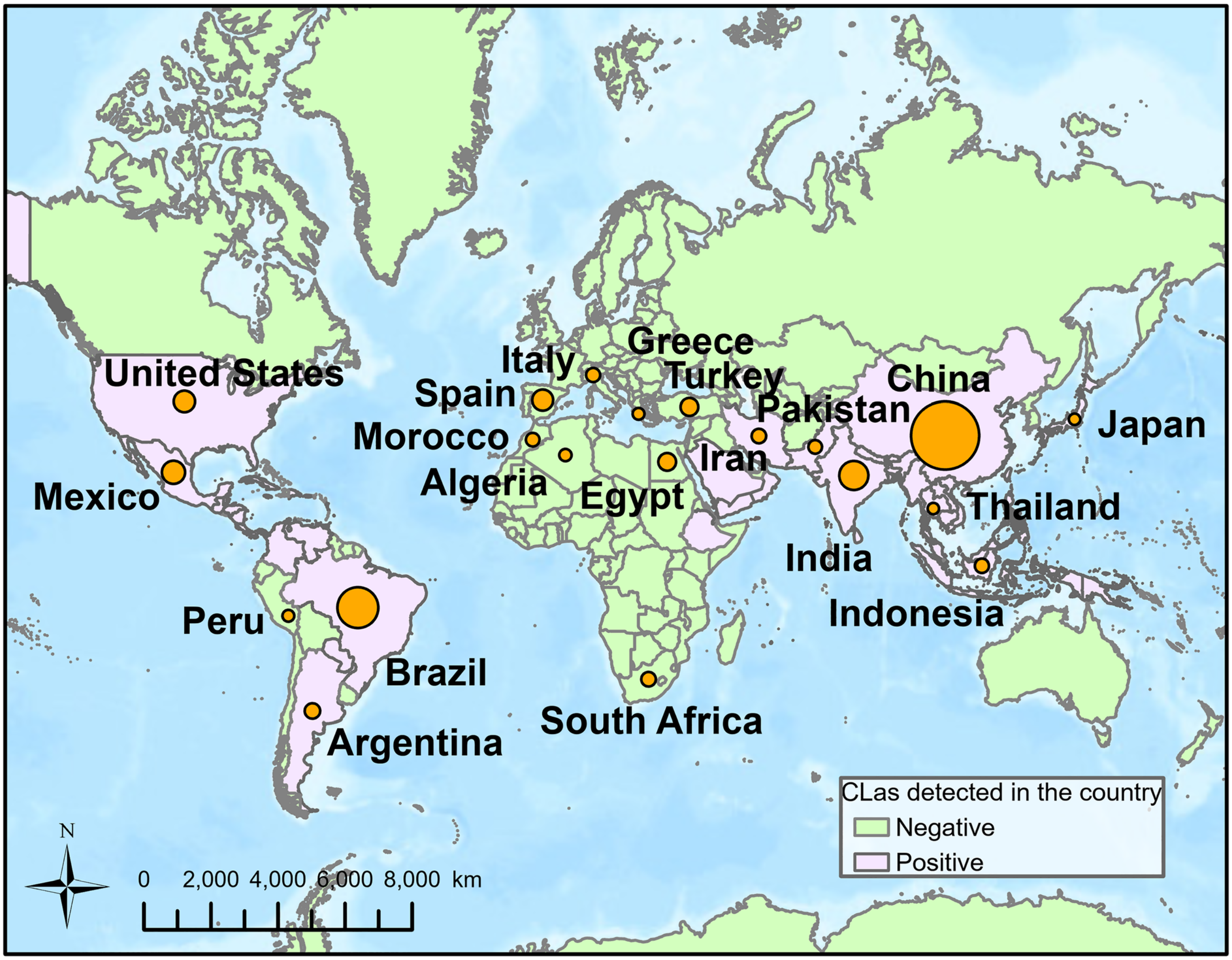

Fig. 1 Current distribution of "*Candidatus* Liberibacter asiaticus" (*C*Las) in citrus-producing countries. Countries that have detected *C*Las are shown in pink, and countries that have not detected *C*Las are shown in green (CABI, 2020a). The orange circles are proportional to the total citrus production (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 *C*Las; and nine of them (Algeria, Egypt, Greece, Italy, Morocco, Peru, South Africa, Spain, Turkey) have not detected *C*Las

"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.

3 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 (Fig. 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).

Like citrus health provision, sustainable management of common-pool resources (CPRs), such as forests and fisheries,

Fig. 2 Status of the HLB epidemic in Brazil, Mexico, the United States and Argentina. Countries that have detected *C*Las are shown in pink, and countries that have not detected *C*Las 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 nine 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

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), 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.

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 2).

3.1 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 & 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).

3.2 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).

3.3 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

Table 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 2B. Congruence between appropriation and provision rules	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 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

majority vote (≥51% of acreage) and are subject to the rules defined by the elected PCD board of directors (UCCE, 2005).

3.4 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

Table 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 Manageme-nt 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 collabora-tion 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. Assessmen-ts 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 collabora-tion 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) estab-lishes rules for HLB in collabo-ration with the California Department of Food and Agriculture (CDFA)						
4A. Monitoring users	No	Monthly reports of area treated coordinately	–	No	Reports of area treated coordinate-ly 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 con-trol advisors (PCAs) hired by growers

Table 2 (continued)

Design principle	São Paulo (Brazil)	Mexico	Entre Rios (Argentina)	Florida (USA)	Texas (USA)	California (USA)
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)

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).

3.5 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.

3.6 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.

3.7 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.

3.8 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.

4 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 illustrated in Table 3. 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

Table 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 (Legg et al., 2017)
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

highlighted the need for alternative institutional arrangements (Singerman & 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 four 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 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 & 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).

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.

5 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 & 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 & 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.

6 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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