Cooperation and Coordination in Plant Disease Management

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ABSTRACT

Scaling of management efforts beyond the boundaries of individual farms may require that individuals act collectively. Such approaches have been suggested several times in plant pathology contexts but rarely have been implemented, in part because the institutional structures that enable successful collective action are poorly understood. In this research, we conducted in-depth interviews with hop producers in Oregon and Washington State to identify their motivations for and barriers to collective action regarding communication of disease levels, coordination of management practices, and sharing of best management practices and other data for powdery mildew (caused by *Podosphaera macularis*). Growers were generally open to and engaged in communication with neighbors and others on disease status in their hop yards and some evidence of higher levels of information sharing on management practices was found. However, growers who had developed extensive knowledge and databases were reluctant to share information viewed as proprietary. Relationships, trust, and reciprocity

were facilitating factors for communication and information sharing, whereas lack of these factors and social norms of independence and pride in portions of the grower community were identified as impediments. Given the heterogeneity of trust, lack of confidence in reciprocity, and weak shared norms, communication of disease risk and coordinated management may be most successful if directed at a smaller scale as a series of neighborhood-based partnerships of growers and their immediate neighbors. Developing a disease reporting system and coordinated disease management efforts with more producers and at larger spatial extents would require formalized structures and rules that would provide assurance that there is consistency in disease data collection and reporting, reciprocation, and sanctions for those who use the information for marketing purposes against other growers. Given the analyses presented here, we believe there is potential for collective action in disease management but with limitations on the scope and nature of the actions.

Pest management efforts can be applied at varying spatial scales ranging from the subfield, field, and farm level, but also regionally and at the landscape level. Most commonly, disease management strategies are directed at field or perhaps farm scales. However, plant pathogens and other pests are readily dispersible over multiple spatial scales; therefore, intervention efforts at scales larger than the boundaries of individual fields or farms could be most appropriate and effective depending on the dispersal characteristics of a pathogen or a vector (Irwin 1999; Mahaffee and Stoll 2016). Long-distance dispersal is especially common in aerially disseminated organisms with large reproductive capacity and short generation times, which result in some of the most explosive and damaging epidemics (Severns et al. 2019). Thus, an active area of research is focused on pathogen dispersal and aerobiology and on consideration of long-distance dispersal in disease networks and disease risk models (Aylor 2017; Gent et al. 2019a; Mahaffee and Stoll 2016;

Meyer et al. 2017; Yuen and Mila 2015). The adoption of recommendations arising from such research may be best implemented on an area-wide basis.

Area-wide pest management is a concept that developed mostly in entomology and emphasizes targeting an entire pest population within a defined geographic area (Carrière et al. 2012; Klassen 2005; Tabashnik et al. 2010; Witzgall et al. 2008). There are several examples of implementation of, or policies advocating for, area-wide management of plant diseases. Some notable instances include quarantine and eradication measures (Cunniffe et al. 2016; Kahn 1991), deployment of host resistance in space and time (McDonald and Linde 2002; Mundt 2014), increased landscape heterogeneity (Margosian et al. 2009), coordinated management of primary inoculum (Bassanezi et al. 2013; Bergamin Filho et al. 2016; Peterson 2018) and vectors (Jones 2004; Milne et al. 2018), synchronous planting (Cabunagan et al. 2001), and host-free periods (Jones 2004; Wisler and Duffus 2000). In most cases where area-wide management of plant diseases has been implemented, this has involved actions by government agencies (e.g., insecticide applications for vector control in noncrop lands) or statutory requirements for participation (e.g., host-free periods). Less common are area-wide management approaches that require participation and actions by individual growers, although some successful examples exist (Bassanezi et al. 2013; Legg et al. 2017).

Why are collective efforts so rare in plant disease management? Many problems and goals of societies require collective action from people or organizations with potentially competing interests and values. Situations in which there are differing rewards for cooperation and individual gain often are presumed to belong to the class of problems often described as the “tragedy of the commons” or “prisoner’s dilemma” (Hardin 1968; Ostrom 1990; Poundstone 1992). A pest organism that moves freely from farm to farm can be considered a “negative common property,” which is “...one owned in common and exploited under conditions of individualistic competition,” as stated by Lazarus and Dixon (1984) and credited to

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Gordon (1954). Note here that although Lazarus and Dixon (1984) referred to pests as negative common property, common property and public goods are now distinguished by scholars based on exclusion and subtractability of use (Ostrom 2005). Public goods refer to those where one person's consumption is nonsubtractive from the total available to others and exclusion is not feasible. Air and public radio are two examples of public goods. Common property, also referred to as common-pool resources, typically describes economic goods with high exclusion costs and where one person's consumption is subtractive from the total resource. Grazing land, fishing grounds, and groundwater resources can be examples of common property. Individual growers act to reduce disease issues individually, seeking to minimize costs, but this leads to a potentially suboptimal condition (referred to as a Pareto inferior condition) when overall costs to other growers also are not minimized, as disease resulting from dispersed inoculum is a cost internalized to other growers (Lazarus and Dixon 1984; Lemarié and Marcoul 2018). Whenever an individual cannot be excluded from the benefits provided by actions of others, each person is motivated not to participate fully in the collective action but to "free-ride" on the efforts of others (Ostrom 1990). For example, distrust in whether other growers would participate in an area-wide management program for citrus Huanglongbing disease was the most frequently cited concern citrus growers had about joining the program (Milne et al. 2018).

A case study where collective action could be applied to improve management of a plant disease can be found with powdery mildew of hop (caused by *Podosphaera macularis*) in the U.S. Pacific Northwest. There are annually recurring points in the disease cycle where collective action would enhance disease control. Management of the disease is typical of most powdery mildews in that a combination of practices is recommended, including selection of resistant or less susceptible cultivars, sanitation measures to reduce primary inoculum, cultural practices that moderate canopy density, and fungicides applied preventatively (Gent et al. 2008, 2012; Mahaffee et al. 2009; Nelson et al. 2015; Probst et al. 2016). However, a unique aspect of the disease biology is that the sexual stage of *P. macularis* is not known to occur in the western United States because only one of the two requisite mating types of the fungus occurs in the region (Wolfenbarger et al. 2015). This constrains overwintering of the pathogen to infection of living host tissue, provided by crown buds, resulting in bud perennation and the development of "flag shoots" in the following year (Fig. 1) (Gent et al. 2008; Mahaffee et al. 2009; Royle 1978). Flag shoot occurrence is a relatively rare event in the western United States, especially in Oregon where the pathogen persists in a small subset of yards (Gent et al. 2019b). In Oregon, only 0.05% of hop plants produce a flag shoot and only 3.3 to 6.7% of hop yards harbor flag shoots at any level (Gent et al. 2019b). This is a bottleneck in the pathogen lifecycle that can be targeted for better management of the disease in individual yards but also at larger spatial scales.

Powdery mildew tends to be very localized in the early stages of epidemics because of the infrequent occurrence of flag shoots but spreads rapidly by airborne conidia within and between an increasing number of yards as the season progresses (Gent et al. 2019a). Thus, there is a potential community impact of flag shoot occurrence depending on where affected yards are located in the landscape. If conceptualized as a negative public good, the boundary of spore dispersal is defined probabilistically based on factors that include strength of the pathogen source, wind, the pathogenic race of the fungus present, and distance between hop yards. The "resource" is subtractable in the sense that the reduction of flag shoot occurrence reduces disease attributable to dispersal to other yards, with the precise relationship again defined by a probabilistic statistical function (Gent et al. 2019a). However, there is uncertainty in knowing the boundary and subtractability of dispersal if the location and severity of disease on other farms is unknown or unreported. Therefore, cooperation in disease reporting and sharing of management practices could be beneficial to the

entire community of growers, as could coordinated management to eliminate or reduce flag shoot occurrence, as we discuss later.

In envisioning ways to improve cooperation and collective action in disease management, it is imperative to recognize that multiple factors may influence the likelihood and structure of successful cooperation, and universal solutions to complex social-ecological systems do not exist (Ostrom 2007). Agrawal (2001) reported that no less than 30 variables have been posited as affecting the organization and management of common property. Although not all of these variables are relevant in every context, cooperative behavior characteristically is influenced by many structural variables (Ostrom 1998) and contextual factors such as markets, demography, and regulatory aspects (Agrawal 2001). Hagedorn (2013) notes that collective action invariably involves an interplay between the resource and how it is used ("nature-related transaction") and characteristics of the individuals or organizations involved. These factors are multifold and interacting, involving basic social differences in values and trust of others, economic motivations, institutional and structural factors, agency, and power.

Several extensive analyses of common-pool resources and theoretical frameworks for social-ecological systems exist (Baland and Platteau 1996; Binder et al. 2013; Ostrom 1990; Wade 1988). Cooperation is predicted to depend sensitively on social factors and context (e.g., Cabunagan et al. 2001; Ostrom 2003a, 2007). An overly simple, yet coherent causal framework and theory of collective action has been proposed (Ostrom 1998), along with extensions of this theory (Hagedorn 2008, 2013), that incorporates characteristics of actors, the nature of the problem, institutions, and governance structures that act to influence cooperative actions (Fig. 2). A central aspect of Ostrom's (1998) behavioral theory of cooperation is trust, which influences expectations for reciprocity and the level of cooperation in a positive feedback. Trust is theorized to be influenced by physical, cultural, and institutional variables, mediated by structural variables that depend critically on communication and the likelihood that communication will lead to agreement on collective action. More generally, variables affecting the outcome of collective action can be viewed as a hierarchy, with the highest level of the hierarchy defined by interactions and outcomes of attributes of the resource system, as well as the resource units, users, and governance system within the specific social, economic, and political setting and ecosystem (Ostrom 2007). The variables at the highest level can be decomposed to the variables nested at a second or third level, which influence the likelihood of collective action.

Fig. 1. Example of hop shoots in early spring with extensive colonization by *Podosphaera macularis* as a result of bud perennation. The inset is a close-up of the flag shoot near the center of the plant.

The rich literature base and theoretical basis for collective action in natural resource management stands in contrast to the near absence of literature on this topic in the context of plant disease and pest management. Trust and reciprocity are expected to be central to cooperation in agricultural contexts, as found in some empirical studies (Milne et al. 2018), but there are theoretical reasons to question how trust develops within specific grower cultures that value independence and privacy (Graham 2014; Lubell 2007). Furthermore, growers in general value personal experiential knowledge (Burke and Running 2019), with this being especially salient among hop growers (Sherman and Gent 2014). Growers' perceptions of costs and effectiveness in turn influence decisions to adopt cooperative actions (Lubell et al. 2011). Other barriers to cooperation may involve lack of communication, as mediated by group size, hegemonic distribution of resources and benefits for cooperation, views of trusted advisers, and lack of awareness or trust in the efficacy of collective actions (Lubell et al. 2011, 2013; Roche et al. 2015; Sherman and Gent 2014). Clearly, there is a lacuna of scholarship on conditions that influence collective action in disease management and how to encourage sustained coordination among actors (Parsa et al. 2014; Singerman et al. 2017).

We examined social and contextual factors that enable or prevent collective action for management of powdery mildew of hop. The pathosystem has several idiosyncratic aspects, but nonetheless provides an instructive case study that has parallels to other systems because of the potential role of collective action in communicating and mitigating disease risk. In this article, our objective is to identify factors that provide motivations for and impediments to cooperation and coordinated management efforts with other growers. We first present background information on the production and pathosystem important to understanding the disease biology, research sites, and approach to this research. Next, we inductively examine transcripts of semiguided grower interviews to identify concepts and themes of factors motivating or limiting cooperative efforts. We situate the work within the broader framework of community-based natural resource management and provide specific recommendations that can guide others when considering organizing cooperative disease management efforts.

MATERIALS AND METHODS

Background on the host, disease, and management. *Hops and hop production.* Hop (*Humulus lupulus*) is a long-lived perennial plant, with annual shoots, which is grown primarily for

brewing beer (Barth et al. 1994; Neve 1991). The plant is dioecious and the commercial value of the crop is the in female strobili (cones), which are the source of dense glandular trichomes that produce oils and soft resins that are antimicrobial preservatives and add bitterness, aroma, and flavor to beer. Most commercial hop production occurs in the U.S. Pacific Northwest in the states of Washington, Oregon, and Idaho. Most of the crop is forward contracted, and contracts stipulate quality metrics that are important to brewers—for instance, cultivar purity, brewing chemistry, cone color, and subjective sensorial attributes such as aroma. Both yield and quality factors are critical to growers. Contracting most often is through a hop brokerage company, although some growers establish production contracts directly with brewer customers. The largest brokerage companies in the Pacific Northwest also have active plant breeding and brand management programs. Production of proprietary cultivars therefore tends to be through only one company, which may dictate additional production and quality standards and also provide information to contracted growers.

Hops are expensive to produce and require specialized trellis systems, equipment, and facilities that can limit new growers from entering the industry (Mahaffee and Pethybridge 2009). A full yield is not obtained until the second or third year after planting, although nearly a full crop can be attained in the year of planting in Washington State. Because of this and consolidation over time, there are only about 100 large-scale hop producers in the Pacific Northwest and the largest farms tend to be in Washington. Large-scale growing operations in the United States tend to be well established. In 2012, for example, <1% of large-scale farms were considered beginning farms (U.S. Department of Agriculture Economic Research Service 2017). In the present study, nearly all participating hop farms have grown the crop for multiple generations.

Powdery mildew and disease management. Powdery mildew is among the most damaging and costliest diseases of hop in the western United States. The disease causes crop damage primarily because of the cone phase of the disease, which can reduce cone yield and levels of bittering acids during severe occurrences (Gent et al. 2013; Mahaffee et al. 2009). Perhaps equally important to the damage caused by direct yield losses are effects on brewing quality and subjective measures of cone quality such as aroma perception and color (Gent et al. 2014; Hysert et al. 1998; Neve 1991). Defects in these quality attributes can lead to crop rejection, depending on market conditions and the standards of the contracting brewer (Mahaffee et al. 2003).

The disease was absent from the Pacific Northwest until the mid-1990s as a result of quarantine measures and the physical isolation of the industry (Mahaffee et al. 2003; Ocamb et al. 1999). Since the introduction of the pathogen, the source of which remains speculative, powdery mildew has spread across the main production regions in Washington, Oregon, and Idaho and now becomes epidemic annually (Mahaffee et al. 2003; Turechek et al. 2001).

As noted previously, disease management is multifaceted, but many specific disease management strategies are not available to growers because of the perennial nature of the crop and unique horticultural requirements for maximum production. For instance, growers have limited opportunity to select resistant cultivars because the crop is perennial and brewing characteristics dictate demand for specific cultivars. Furthermore, few cultivars in the Pacific Northwest actually are resistant to the disease because two important sources of host resistance were overcome by virulent races of the fungus (Gent et al. 2017; Wolfenbarger et al. 2016). Therefore, disease management relies heavily on cultural practices and chemical control measures, with the latter being applied on average 5.1 to 7.7 times per season in Oregon and Washington, respectively (Gent et al. 2012; Sherman and Gent 2014). Fungicide use can be more intensive in susceptible cultivars (Gent et al. 2019b).

For horticultural reasons and also for disease suppression, the first flush of hop shoots typically is removed in late winter to early

Fig. 2. A simple causal theory of cooperation adapted from Ostrom (1998) based on core relationships of trust, reputation, and reciprocity, as influenced by exogenous and endogenous structural variables. Exogenous structural variables are noted in italics and are linked by dashed arrows to endogenous structural variables. Endogenous structural variables are linked by solid arrows to core relationships of trust, reputation, and reciprocity (noted in bold). Positive and negative associations are noted with corresponding symbols.

spring by pruning (Probst et al. 2016). Pruning may be conducted by various methods, the most common being chemical desiccation of shoots by herbicides (“chemical pruning”) or by mechanical methods (“mechanical pruning”). Chemical pruning only removes shoots that have emerged, whereas mechanical pruning removes both emerged shoots and the associated surface crown buds (Fig. 3). Both approaches suppress powdery mildew depending on the thoroughness of the pruning practices employed (Gent et al. 2012, 2019b; Turechek et al. 2001). However, some proportion of flag shoots may persist after chemical pruning and mechanical pruning tends to be more effective (Gent et al. 2018a, 2019b). Nonetheless, chemical pruning is less expensive (approximately half the cost) and can be applied more rapidly over large areas, particularly when drip irrigation is used (Probst et al. 2016). Thus, chemical pruning is more commonly used in commercial production compared with mechanical pruning in the western United States (Gent et al. 2019b).

Disease spread modeling indicates that powdery mildew spread in Oregon is mostly limited to approximately 2 km in spring (Gent et al. 2019a). Thus, most spread tends to be confined to the same or contiguous farms. However, long-distance dispersal becomes more probable as the season progresses and the disease eventually spreads to affect most farms and susceptible cultivars regionally, independent of whether the pathogen overwintered on those farms (Gent et al. 2019a). Network modeling suggests that the hop yards most central to the network are found on a minority of farms and characteristically are found in dense plantings of highly susceptible cultivars, where a flag shoot or disease was preexistent and pruning was conducted using chemical means (Gent et al. 2019a).

There are several important implications of the overwintering biology and long-distance dispersal. First, as noted previously, there is a community aspect to disease risk as a result of overwintering of the pathogen and also a potential community benefit of sanitation measures. The severity of powdery mildew and efficiency of management efforts, as measured by the number of fungicide applications made, is linked sensitively to where powdery mildew does or does not first occur (Gent et al. 2019b). Because the pathogen overwinters in only a subset of yards, coordinated management of the disease in a subset of yards and farms could be the basis for an area-wide management if sanitation measures were applied uniformly or appropriately targeted to high-risk situations across the region. Second, because of the potential for dispersal of inoculum between yards and farms, communication of disease occurrence and information sharing between growers is important for understanding and appropriately mitigating disease risk. This is most critical for nearby neighbors early in the season, although later in the season communication of disease occurrence and its severity should ideally be among the entire community of producers, given

the potential for long-distance dispersal. Third, disease management efforts that reduce pathogen source strength are predicted to reduce the probability of long-distance dispersal (Gent et al. 2019a). Therefore, within a season, growers who do not yet have powdery mildew would benefit from sharing their best management practices (based on their own experimentation and experience) with growers who do have the disease. The benefit received by the overall community of growers should be improved by participation by all other growers in communication of disease occurrence and coordination in disease management efforts.

We refer to these management implications broadly as cooperation when individuals act jointly for mutual benefit, but more specifically as coordination when referring to standards of organization or conventions that enable cooperation (Calvert 1995). Communication is central to both cooperation and coordination. However, communication is not differentiated theoretically from cooperation, but rather is a form for cooperation and a determinant of coordination. Herein, cooperation and communication are used to describe informal or formal information sharing about disease status, sharing of management practices, and related data growers have collected or learned by experience. These terms are often used interchangeably because communication as a form of cooperation was of primary interest within this research. We use the term coordination to refer more narrowly to intentional, joint actions in disease management, such as synchronization of cultural practices in spring to eliminate overwintered inoculum or chemical control measures.

Research field sites and methods. The research focuses on the two largest regions of hop production in the United States, the Yakima Valley in eastern Washington and the Willamette Valley in western Oregon. The Yakima Valley is a semiarid region, heavily reliant on irrigation. Approximately 72% of all hop acreage in the United States was contained within the Yakima Valley in 2017, which produced 75% of the total U.S. crop (National Agricultural Statistics Service 2017, 2018). Oregon is the third largest hop-growing state in the United States (National Agricultural Statistics Service 2017, 2018). The hop industry in Oregon is centered in Marion County near the state capital of Salem. The climate is maritime west coast, with mild, wet winters and warm, dry summers, which constrains the growing season and the cultivars of hop that can be grown there. The Willamette region has a considerably smaller share of U.S. hop acreage (15%) and produces 11% of the total U.S. crop (National Agricultural Statistics Service 2017, 2018).

In-depth assessments of individual farms and pest management practices were obtained from open-ended, recorded interviews with 20 individuals who work in the hop industry, which took place during the summer months of 2016 and 2017. Participants were

Fig. 3. Various forms of pruning conducted in spring to eliminate inoculum of the powdery mildew fungus. **A**, Chemical desiccation of shoots. **B**, Persistence of powdery mildew after chemical desiccation of shoots. **C**, Top view of a hop “hill” after mechanical pruning physically removed the remnants of the shoots from the previous season and surface crown buds.

selected and invited based on several factors. In Oregon, invitations to participate were made to owners of all the farms located in the eastern extent of the Willamette Valley. These were the same growers whose farms were included in the census sampling for powdery mildew described in Gent et al. (2019a). Additionally, owners of farms immediately to the west of the spatial extent of that study also were invited. These farms and growers were targeted because of their expected relevance of collective action for powdery mildew management in this region. In Washington, sampling was not random but purposeful. Participants included growers whose farms varied in size and were dispersed geographically across the Yakima Valley. We attempted to include at least one small to medium-sized farm and one large farm from each of the Yakima Indian Reservation, Moxee Valley, and Lower Yakima Valley subregions in Washington. There was potential for selection bias in Washington because invitations were made to growers (or farms) that fit our selection criteria but also, we believed, would be willing to participate in any interview based on our experience. The research protocol was approved by the Washington State University Institutional Review Board and was granted exempt status because it was deemed to be low risk to participants.

Qualitative methods are particularly useful for obtaining in-depth assessments at the level of individuals, because these methods allow respondents to indicate not only what they are doing but also their rationale for the actions (Norton et al. 2005). Interview questions focused on several main thematic areas, including background and demographic information, specific pest and disease management practices regarding threats including two-spotted spider mites (*Tetranychus urticae*, one of the most important arthropod pests of hop) and powdery mildew, as well as detailed questions regarding the use of specific chemical tactics and transitions toward less chemical-intensive strategies (Supplementary Data File S1). The interviews ended with unstructured time for participants to bring up other issues that were important to them, and a number of them focused on issues including marketing strategies, economic concerns, and farm labor. Of particular interest for the current discussion was a set of questions that asked participants in detail about motivations for specific changes in their management programs, knowledge about and communication with their neighbors, and their potential openness/willingness to coordinate with other farmers regarding disease threats and outbreaks, particularly with regard to powdery mildew.

All interviews were conducted in person by the first author. The sample was heavily male, as a result of the structure of the industry, but 10% of the participants were women (Table 1). Both of the women interviewed were the main operators of their farms. Participants ranged in age from 23 to 60 years, with a mean age of 43. Participants indicated that most of the farms had been owned and operated by their families for three generations or more. Farm operations ranged in size from just under 170 acres to more than 2,000 acres planted in hops, with an average of 1,242. Yakima

Valley farms tended to be larger than those in the Willamette Valley; the Yakima Valley farms averaged about 1,840 acres, whereas Willamette farms averaged about 646 acres in hops. In order to help maintain the confidentiality of farmers, we categorized farms as small (<500 acres), medium (500 to 1,000 acres), and large (>1,000 acres) scale. Six farms (30%) were categorized as small scale, four were medium (20%), and eight were large (40%) using this schema; two farms were not categorized because participants declined to disclose farm size.

Interviews generally lasted from 60 to 90 min. Participants were interviewed either alone or in pairs, as several chose to have a colleague present to help give a fuller account of their farm's operations. In these cases, the second person included farm co-operators, consultants, or agronomists on staff. All interviews took place in their farm offices on-site, reflecting their preferences. The interviews were based on a series of questions common to all interviews but allowed for follow-up questions based on the answers given.

Interviews were digitally recorded, transcribed verbatim, and analyzed and coded using NVivo qualitative analysis software (QSR International, Burlington, MA). Multiple rounds of coding were conducted by the first and second authors in order to ensure comprehensive analysis. Transcripts were coded for both anticipated themes from the collective action literature and unanticipated themes that arose repeatedly throughout the interview sample, using a grounded theory orientation (Corbin and Strauss 2007). Initial coding focused on broad themes, and subsequent rounds of coding added more detailed categories related to the larger themes (Corbin and Strauss 2007). Field notes regarding the interview settings and respondents were generally recorded within 24 h of the interviews and were included in the analysis. After initial analysis, the findings were discussed in depth with other researchers on the project who had extensive experience working with growers in the two regions, in order to confirm that findings were consistent with their experiential observations. All names of individuals and companies reported herein are pseudonyms in order to preserve the confidentiality of participants.

RESULTS

With regard to powdery mildew prevention and treatment, participants were asked a number of questions about their potential interest in and willingness to communicate with other growers in order to maximize information in ways that would allow the industry to collectively combat the threat. Specifically, they were asked whether they would be willing to share information on disease status, scouting data, and general agronomic data, such as specific inputs and in-house research. Most had some understanding of the ways in which data sharing might benefit their management programs. Yet despite the potential for such sharing to improve crop production and quality outcomes, growers expressed considerable skepticism, concern, and trepidation regarding participation in

TABLE 1. Interview participant demographics

Factor	Responders ^a	Mean	Median	Minimum	Maximum
Age of respondent (years)	19	42.6	44	23	60
Years farming	14	16.7	15.5	4	39
Total acreage	14	1,471.9	1,125	347	3,700
Total acres in hops	18	1,242.2	975	170	3,700
Willamette Valley acres in hops	9	645.6	325	170	2,200
Yakima Valley acres in hops	9	1,838.9	1,800	600	3,700
Male sex (%)	90	—	—	—	—
White (%)	85	—	—	—	—
Farm in family for three or more generations (%)	80	—	—	—	—

^a Interviews were conducted with a total of 20 individuals, nine from Oregon (Willamette Valley) and 11 from Washington (Yakima Valley). Data are presented as the number or percentage of responders unless indicated otherwise. Dashes indicate a statistic was not relevant.

programs that would require them to share detailed data with other growers. In particular, their concerns revolved around a number of important issues that elucidate both the barriers to collective action and the possibilities for its success (summarized in Table 2). In the following sections, we explore several of these issues, including concerns regarding trust and personal exposure within the larger hop-growing community as well as concerns regarding lack of reciprocity and potential for loss of competitive advantages. We end by describing the ways in which growers envisioned the possibilities for addressing these concerns and creating an environment conducive to cooperative information sharing.

Barriers to communication: “Tight lips,” pride, and competition. For many hop growers, the potential benefits of sharing information on disease status among farms was clear. Small-scale Oregon grower Drew Gibbons commented, “Co-ordination would absolutely be helpful... The coordination thing could be tremendously powerful.” Large-scale Washington grower Brian Lambert elaborated on the same conclusion:

In my personal opinion, it behooves us all if we do have a problem cropping up; with a disease like powdery or downy for that matter, it makes sense that we all share in that, and say there is a problem out here, let’s get a hold of it. So if there is some sort of heat map and we could see that and see the problem coming, that could be very positive if it is done right.

Growers acknowledged that sharing data could facilitate coordinated spring pruning practices to reduced overwintering inoculum in ways that they could not in isolation. Small-scale Willamette Valley grower Lucas Harris explained,

I was thinking maybe next year if we could get together with all our neighbors, we might be able to almost eliminate the powdery mildew problem if we could get our pruning set right and things. So, there might be something happening in the more near future because the way it sounded, if it is just the two of us [that] do it, it is still not enough because you have these one or two outliers out there.

As these quotes illustrate, many of the growers could see at least some potential gain from increased communication and coordination regarding powdery mildew threats and mitigation.

Despite their acknowledgments of the potential for improved disease control, however, growers articulated multiple issues that held them back from willingness to participate directly in such information sharing. A number of growers spoke of interpersonal concerns regarding trust, reputation, and the general reserve of farmers as the first set of barriers to communicating and coordinating with fellow hop growers. They repeatedly related these issues to cultural and social norms for growers, particularly

the older generation within the industry, who place value on their independence. Interpersonal concerns were mostly discussed by Willamette Valley growers, the region where farms tend to be smaller and geographically close together. Farmers in this region often voiced interpersonal issues such as reticence and pride as the most salient barriers to communication and cooperation. Large-scale Willamette Valley hop grower Kent Glover commented, “Most people are pretty closed mouthed around here about what they do.” Small-scale Willamette Valley grower Jess Daniels similarly suggested that growers “like to keep things to themselves if they have an issue.”

Several growers suggested that age or generation might play a role in influencing both reticence and openness to new ideas. Washington grower Marc Lyon referred to an “old-school mentality of keep to myself.” Small-scale Oregon grower Lucas Harris described a similar sense that some growers “are pretty tight lipped about what to do sometimes.” One of the younger growers in the sample, Lucas, saw the issue as more prominent among older growers, explaining, “The ones in my dad’s generation probably—they are pretty tight lipped. But I think the younger guys in my generation are a little bit more open about it.” For Drew Gibbons, who had been at the helm of his small Willamette Valley farm for just 4 years, the concern was less about farmers being “tight lipped” and more that they were not open to being exposed to new ideas by their younger contemporaries:

People can be pretty closed minded about stuff. And so they are not—I don’t think they are really that interested. I mean, not to make an assumption, but they are just—people get kind of weird about that stuff.

Q: How?

I think it feels territorial to them, and it is an identity—it is like a pride thing for them. Because they grow good hops too, so who am I to tell them they are doing it the wrong way? I guess it is not the wrong way, but a different way.

Q: Do you think that is because of your age?

Yeah, part of it. And just farmer-to-farmer stuff. I mean, everyone has an ego, but farmers can be very stubborn.

Drew hinted at competition as an underlying concern behind these dynamics but still spoke of them as interpersonal and emotional concerns rather than market-driven issues:

I think ... there is a little bit of resentment just because, you know, as people want to feel that they are right, and if they see another idea or model is working, and they are so adamant that their model is the right way, I think it creates resentment or jealousy even. I

TABLE 2. Common factors that impede and facilitate cooperation and coordination of disease management among hop growers in the Pacific Northwest

Factors that impede			Factors that facilitate		
Code	Interview ^a	Reference (code) ^b	Code	Interview	Reference (code)
Competitive advantage	12	38	Pest threat	11	17
Pride	6	11	Relationships/trust	10	21
Relationships/trust	6	8	Information	6	12
Generation/tradition	5	12	Membership in organization	6	6
Complicated practices	4	7	Location/proximity	5	12
Industry inequality	3	9	Benefits to industry	3	7
Location/proximity	3	4	More resources	1	4
Time	3	4			
Pest patterns	3	3			
Varying viewpoints	2	8			

^a Interview refers to the number of individuals interviewed where this factor was identified.

^b Reference (code) is the number of times this coded factor was identified in the interview transcripts.

don't know what you call it, but it just creates some weird feelings or weird vibes where it just changes the relationship.

According to these growers, cultural issues and personal feelings were among the greatest barriers to sharing information on disease levels and best practices more widely within the hop industry.

Pride was another interpersonal issue that was discussed by a number of growers in both regions, although it was a more common theme among Willamette Valley farmers as well. A number of growers suggested that others would shy away from sharing disease data that might make themselves look bad. Small-scale Willamette Valley grower Bill Nelson commented, "They are embarrassed, I guess. Like somehow they think they have caused it. And maybe they have, but they haven't caused the outbreak, but maybe they have caused the level of infection." Large-scale Yakima Valley grower Larry Taylor also expressed the concern that sharing disease information could be "kind of touchy. First you have to admit you have a problem." Medium-scale Yakima Valley grower Jeremy Watson saw pride working in a slightly different way and expressed concerns that farmers might hold back information in order to avoid losing control over the solution: "Most farmers are fairly independent and they like to do their own thing and don't want to be told what to do too much."

Particularly for Yakima Valley farmers, pride issues overlapped with the second set of issues related to profitability and competitive advantage. Most farmers in this region expressed more concerns regarding the potential for sharing information on disease levels to damage their reputational competitive edge in the market. For Oregon grower Jess Daniels, concerns about market issues were the real reason why growers might be worried about their reputations: "If there are certain issues, some people if they have a problem on their farm don't want people to know in case it will give them a bad reputation." For him, this damage to reputation was a serious concern that went beyond simply pride: "That's the problem. Am I the only one with the issue, or is [*sic*] my hops going to get rejected or something for bad quality? So, I would say that's the biggest barrier for that." For large-scale Washington grower Brian Lambert, sharing information on disease occurrence and severity could either help or hurt farmers, but he expressed concern regarding the possible harm to his farm's reputation:

I think we would find that you are not the only hot spot, and it actually would—everyone would see. Like, okay, everyone has got this problem. Or alternatively, I guess it could point out, oh, boy, I am the only one with this problem. But you do want to make sure it is good data. So if we have a hot spot, if one of our yards is really high in infection compared with others, I don't necessarily—I'm not opposed to sharing that, but I just want to make sure that it is good data, and it is not just an anomaly and then we are getting trashed because of bad data. So that would have to be done right, I think.

In addition to concerns regarding how communicating about their own problems might hurt growers, a number were also reluctant to give away disease management information that might be helpful to them and thus lose a competitive advantage. Particularly among Yakima Valley farmers, it was common for growers to suggest that there were limits to what they would be willing to share. This issue was most salient for the largest-scale growers, who often had the resources and staff to collect sophisticated data and databases in-house on issues such as nutrient management, irrigation scheduling, and other highly detailed management practices. For these growers, this information represented a competitive advantage that many were reluctant to compromise. Large-scale Yakima Valley grower Larry Taylor explained this concern as, "I'm investing a lot of money trying to find out a solution. Why should I give it to you for free?" Large-scale Yakima Valley grower Brian Lambert similarly

argued, "I think there is [*sic*] certain business practices that from a competitive standpoint, yes, you would want to keep that confidential to some degree, especially things that you have invested a lot of time in developing on-farm." Large-scale Yakima Valley farmer Kyle Anderson saw this attitude as central to being savvy in business: "I don't know that I would just let any old farmer come in and look through our entire agronomic database, but I don't think Ford would let Chevy come in and review everything either. So, there is some stuff that I would say is proprietary to us."

For medium-scale Washington grower Colin Sawyer, fear of helping the competition was a reason to limit sharing: "So, all this free and open talk—there is a couple of things I am doing that I would like to keep to myself." He explained,

The hop industry is just like any... So, it is just like a human organization. There is [*sic*] cliques, politics; some growers are aligned with other growers and not aligned with other growers. I wouldn't say there is a debilitating outright competition, but there is definitely competition and I'm definitely aligned closer with some growers than I am with other growers.

For Colin, these issues were more economic than personal:

I would say it is not a personal thing in the slightest. I get along with everybody. I love all the farmers in the hop industry. I truly do. I would say it is more about marketing. Certain growers are aligned with certain sales desk kind of organizations. And I am a very independent hop farm. I am not aligned with any one merchant or any—I am not owned at all... [Other growers] have the proprietary hops.... So when I grow their hops and I knock it out of the park, I pay them more royalty. So, they are making money off me. And I'm not bitter about it at all, but just I don't need to share with them how I knock it out of the park.

Larry Taylor argued that distinctions between ownership models were unimportant, however, and that all growers competed with each other regardless:

Even though we are owned by the dealer we have, we still compete with other farms and we have to stay competitive. Things are great right now with craft brewing, but as soon as the spike goes—or the curve goes the other way—you know, it gets tough and it gets competitive.

Growers in both regions felt that there were a number of barriers that made sharing information risky for them, including social norms, pride and shame, and market concerns such as the potential loss of competitive advantage. Even though many felt that they would enjoy the benefits of better communication, sharing of best practices, and coordinated management, these social and economic issues made many reluctant to pursue these themselves. On the other hand, a number of growers felt that if there were ways to address and minimize some concerns, they might be open to them. Their comments, as the following section will illustrate, speak to the need for structural support and strong leadership as key to establishing institutions to address these barriers effectively.

Trust, reciprocity, and the potential for collaboration.

Despite the barriers to cooperation, a number of growers suggested ways to design a program that allowed them to share information and coordinate disease control in mutually beneficial ways. At least a few growers could imagine sharing information on best practices for disease management in a safe setting, which for them was often defined by trust and reciprocity. Large-scale Washington grower Eric Lang commented, "I guess I'm just a little bit more of a collaborator. And as long as they are collaborating with me, I'm more than willing to collaborate with them." For growers like these, the potential for information sharing as a positive tool to manage

powdery mildew could be realized through developing and encouraging reciprocal relationships between competitors. As this section will explore, their thoughts on the issue provide insight that can be helpful in crafting programs that allow growers to share information effectively and avoid prisoner's dilemma and free-rider concerns. The growers saw trust and reciprocity as central to cooperation and avoiding potential harms.

A number of growers discussed the importance of having good relationships with others, which builds trust and reciprocity in a positive cascade (Ostrom 2003a), as a first step to this type of cooperation. Yakima Valley consultant Brett Green explained that the nature of personal relationships in the hop industry presented both a barrier and an incentive to open communication:

I think that it'd be advantageous if they [shared information], but in my experience, there are certain areas that do that and certain areas that it's never going to happen.

Q: And it's never going to happen, why?

Just for ... grower relationships, past histories. I got certain areas where they are always talking about those things and others where it isn't going to happen.

Washington grower Brian Lambert also discussed this concern, explaining that with regard to communication and cooperation,

It is kind of a strange deal. It depends on how good of a relationship you have. We have got neighbors that, yeah, we see them, sit and chat, and talk exactly about what we have got going on, and we have got others that don't really want to share a whole lot. So, it just kind of varies. It depends on the person and the relationship you have with them. Typical human interaction stuff.

Despite their ambivalence regarding communication and information sharing, most growers did communicate openly with some growers within select networks on their disease issues, and they discussed regular habits of sharing information on production practices with trusted friends and neighbors. Oregon grower Jess Daniels described having such a mutually beneficial relationship with his neighbor:

I talk to the neighbor a lot about our chemicals. We talk back and forth. If I have a problem, I let him know right then so he can start checking his and vice versa... We talk almost every day.

Q: So you guys share information about pests?

Yeah. Any pests or mildews or anything that we have. We try to let each other know so we can both stay on top of the game. Because if he is having a big problem, it is probably going to come my way, you know. So for both of us to stay ahead of the game is better.

Large-scale Oregon grower Kent Glover explained that he also already shared information openly with farmers he trusted:

There are some that I am more friendly with than others. And I will go bounce things off of them, and I'll bounce things off of us. And some of it is being neighborly. They are looking at our field and looking at their field and going, "I wonder what they are doing. What are you guys doing? Or what do you think we should do?" And I will say, "This is what we did. And by the way, that field over there, what did you do there?" So, it is kind of that.

Growers in both Oregon and Washington noted that communication of disease status and sharing information on best practices was mutually beneficial and already occurring on a small scale.

Most growers could point to some set of contacts with whom they regularly shared information. Washington grower Larry Taylor explained that sharing occurred regularly when growers had a "good relationship": "We talk to other growers, and we talk to other consultants that aren't consulting for us and ask questions, and we try to share as much as possible just because it benefits our neighbors and us. So, we try to have a good relationship with everybody." But Larry made a distinction between this type of information sharing and coordinated management of powdery mildew:

I would say there is probably not a lot of coordination. Just communication as to what they are seeing. Or maybe even if they are using a certain pesticide that works better. We will ask that. Some are pretty tight lipped about it. So mainly communicate. And that can sometimes be weekly. Some of the farm managers have very good relationships, and I will talk to the neighbors two to three times a week depending on what's going on.

Not only were growers more likely to share information on best practices and disease levels than attempt to coordinate management efforts across farms, but even cooperation in information sharing had its limitations. In addition to repeatedly stating preferences for communicating with trusted friends and neighbors, growers also expressed serious concerns about reciprocity and free-rider problems that limited their openness to large-scale information sharing. Washington grower Eric Lang explained that, "If you are not going to share, they are not going to share with you very long, or vice versa. So, there is a handful of growers I have a great relationship with. I'll share any of my results with them, and they do the same with me." He went on to describe his willingness to share as being influenced by the combination of the relationship itself and the nature of the data, and like others, expressed concerns about sharing information that he considered proprietary:

If I thought it was something that really almost fits in the category of common knowledge, right, that can be shared with the whole industry. There is no problem there. If it is something that took a lot of blood, sweat, and tears, and years, and years of stubbing your toe and making mistakes to discover—once again, I'll share that kind of data with someone that would share the same thing from their side to me, any day. But the grower that wouldn't even think about sharing that, much less something that is much easier—I just am reluctant to work with folks like that. Because when they don't see the benefit of a two-way street, it is just difficult... If I'm going to help you, I would expect you to help me. It is just a sense of fair play.

As growers repeatedly stressed, their willingness to share information with other growers, particularly those with whom they did not share preexisting relationships built on trust, was limited by fears of competition and lack of reciprocity.

Institutional structures for communication and cooperation.

In order to work around these barriers, growers had several suggestions for institutionalizing communication and coordination and thus ensuring equal participation by all—or by as many as possible. Several gave concrete solutions to both encourage participation and facilitate equal contributions within the sharing network. For large-scale Oregon grower Kent Glover, the major barriers were logistic, specifically having the staff and resources necessary to collect the sharable data:

The challenge we have in Oregon is smaller farms. So, they are more owner-operated. If you get a big enough farm, you end up with more staff. Then you can start having those people, like, if you had a website or if you had some way to go out and be better at saying,

“Hey, this is what we are doing,” rather than you being the guy doing a lot of jobs. Right? So, it is a time issue, I would think, in Oregon. And I would say there are a handful of farms that probably have more staff now than they used to. That can help maybe start that. And I would think those would be strong farms to start with.

Kent went on to suggest that a formalized disease reporting system and coordinated spring management program might be better received if there was more support for small farmers: “Maybe a few more dollars to let this intern or this person go out and be helpful with another group.” The need for institutional support was echoed by Washington grower Larry Taylor as well, who suggested that public universities might be able to step in and play this role: “I think there could be more collaboration with universities and the farmers than there is.” Cooperative extension was not identified specifically by growers as having a role in the process, likely reflecting the lack of extension personnel working closely with the hop industry in the region.

Regardless of where the support came from, growers agreed that collaboration would only be successful if participation was high. Yakima Valley grower Kyle Anderson stressed the importance of large-scale participation and some form of anonymity when sharing disease data:

We ... would be very, very interested—if it were an industry-wide thing and we were seeing, you know, other people’s data—even if the data was scrubbed and anonymous but you could see kind of geographically where some hotspots were, we would absolutely 110% be interested in being part of an industry-wide effort.

The idea of mass participation as necessary to eliminate the free-rider problem and concerns regarding loss of competitive edge was important to many growers. A number suggested the importance of having strong leadership to encourage participation by all. Oregon grower Drew Gibbons argued for “some sort of committee there or some sort of advisory workshops or something” that could be led by respected growers and university experts: “There is [*sic*] a couple of people that are respected by all, that have done a good job building those relationships.” He went on to muse, “I could see a couple of growers leading it with maybe some support from the academic community to sort of substantiate the claim.”

In addition to strong leadership to encourage participation, growers also envisioned having common protocols and monitoring to ensure that disease data sharing and coordinated pruning practices were robust and verifiable. Willamette Valley grower Lucas Harris explained the necessity of “making sure [a spring pruning treatment] happens, because some people say, yeah, yeah, I did it, and then only did it halfway or didn’t do a very good job. Or [we] have to have, like, a training to make sure everybody does it the same.” Yakima Valley grower Brian Lambert also raised this concern, explaining that he would only participate in cooperative efforts if he was sure that the data he received were as good as the data he shared:

However, that data is being collected and turned in would be a concern. Because I know, for example, we are very intensive with our scouting program. We bring interns in each year, and that’s what they do—that’s all they do. But I also know there is [*sic*] growers that their scouting is they either rely on their field men or their scouting involves them driving and walking out in the yard and looking around for a bit and being like, “Okay, this is what we got.” There is [*sic*] different levels. That’s why I say it would have to be good data. You would have to bring some consistency to the way it is collected and reported. And I think that might be the biggest challenge, really ... figuring out how you do that and make it consistent.

For Lucas, the answer to these types of concerns was also good leadership. He suggested that training should be provided by “somebody who has a track record that they have done it right.” Combined with others’ comments, this points to the possibility of forging trusting relationships through a program that provides resources, monitoring, and leadership within a structure that reinforces both participation and reciprocity.

Existing networks facilitating cooperation. In addition to these suggestions on how to institutionalize information sharing on disease levels and management practices on a larger scale, growers also revealed that the various hop associations and organizations with which they are currently involved facilitate communication. For instance, Oregon grower Jess Daniels indicated that a state hop commission was a way for growers to share information about their pest management programs:

I mean, there is about four or five of us hop growers that go to the hop commission meetings every month, and that group seems to be more open than other people. Yeah, kind of a core group at least for our farm that we talk to bounce ideas off or find out what they are doing.

When asked about sharing more detailed agronomic data, Brian Lambert suggested that members of hop brokerage companies often share this information as part of best management practice expectations:

Within reason. Most of the stuff we are pretty open with, and through our association with [a hop broker company] they have a best practices program and we do a lot of sharing within that program. ... We do have programs where we do share information with other growers. So, we are pretty open. I think we would be willing to expand that with our group.

The evidence suggests that these organizations do help facilitate communication and cooperation, but they do this for those who are members of the particular organization. Alternatively, membership may operate as a barrier to the sharing of information with those who are nonmembers. This further evinces that a more inclusive institutional structure may be needed in order to overcome, or even potentially avoid, the barriers to cooperation and coordination that growers experience.

Together, hop growers provided evidence that there is informal, but regular cooperation in the form of communication of disease status, sharing of some production practices, and in more limited cases coordination of disease management with immediate neighbors and those belonging to the same hop organizations. They also posited elements of the institutional structures needed to avoid pitfalls associated with public goods dilemmas. Regardless of their skepticism and individual concerns, most growers did see the potential that such efforts could benefit them all. Large-scale Washington grower Joel Russell put it succinctly: “Most of them want to help each other. And we are here to grow together and to get by together.” Eric Lang similarly suggested that a disease reporting system could work “because they should be able to see the benefit of seeing where pressures are. Not just powdery mildew but mites and a lot of different things. So, I think that can only be a good thing.” Although most growers saw multiple challenges to creating such a program, they also believed in its potential.

DISCUSSION

Problems of social-ecological systems typically are complex and involve nonlinear, multivariate relationships that may be dynamic over time and space (Ostrom 2007). Attributes of the specific public good, its allocation, and policy rules produce diverse incentives for individuals to act collectively or not (Ostrom 2003b). Thus, detailed understanding of the problem is critically important because

generic policy recommendations are likely to fail. This research is a first step toward understanding the specific context and incentives of growers toward developing institutions for higher levels of cooperation such as data sharing and coordinated management in the context of disease management in the hop powdery mildew pathosystem. Each of these aspects of collective action are varied in their attributes and were viewed with different levels of optimism or skepticisms by the growers. However, we identified two foundational aspects for any of these collective actions in this case study: the need for trust and reciprocity. Many empirical studies and theories point to the centrality of trust and reciprocity in enduring institutions of collective action, including some examples in plant pathology contexts (Milne et al. 2018). Ostrom (2003a) emphasizes that cooperation involving a common property is heavily dependent on trust, reciprocity, and reputation. Suboptimal group outcomes are found in experimental settings when subjects make independent and anonymous decisions with common-pool resources (Ostrom 2007). In numerous studies and settings, including face-to-face communication within this process substantially, and positively, influences outcomes. Face-to-face communication is essential for group members to determine what they should do and to establish norms, in part because face-to-face communication increases trust and reciprocation, reinforcing and increasing these factors over time. The hop growers seemed to recognize the importance of personal relationships in the informal communication and co-operation networks that presently exist, as reported here and elsewhere (Hillis et al. 2016; Sherman and Gent 2014). The growers repeatedly stressed relationships, either personal and/or professional, and reciprocation as facilitating factors for those whom they communicate with and the lack of these factors as barriers to collective action with other individuals.

Counterpoised to the relationships necessary to facilitate collective actions in disease management, however, are social norms present in portions of the grower community that could be barriers to collective action. Some growers spoke of valuing their independence and taking pride in their current farming practices, as well as skepticism with regard to adopting others' practices and innovations. Participation in any collective action, whether communicating disease levels on their farm, coordinating management, or collaborating on best management practices, are counter to these internalized values. Norms of behavior reflect how individuals value actions or strategies in and of themselves (Ostrom 1990). Strong, shared norms are positively associated with collective action, as individuals may feel regret or guilt when a commitment or promise is broken or experience social pressure from a group to maintain commitments. Strong norms also influence how costs and benefits incurred from individual actions influence commitment to a collective effort. When shared norms are strong, only a large payoff for acting opportunistically against the best interests of the group may motivate an individual to act independently. In settings where shared norms are weak or shared only by a minority of individuals, as may be the case in our example, the cost-benefit analysis shifts toward favoring individually opportunistic behavior, and long-term commitments to collective action become more difficult to sustain (Lubell et al. 2011). Where we found evidence of shared norms in the present study, these tended to be associated with personal pride and self-sufficiency. Given this, we expected that a high level of voluntary participation in any collective action would be difficult to establish or sustain with a large group of independent growers.

An important aspect to consider when formulating institutions that would facilitate collective action is the scale of participation necessary for communication, coordinated management, and/or cooperation to be impactful. As noted previously, most spread of powdery mildew in spring initially is localized, typically at the scale of within individual farms and those directly adjacent (Gent et al. 2019a). Therefore, although there are benefits to scaling collective management actions up to the landscape level, there is still value in

collective action at smaller, "neighborhood-based" levels. A somewhat similar approach has been implemented for citrus Huanglongbing disease in California, where smaller groups of growers are connected socially through a group leader, such as a pest-control adviser, who coordinates management efforts for the psyllid vector and disease (Milne et al. 2018). In the present example, given the heterogeneity of trust, lack of confidence in reciprocity, and weak shared norms, communication of disease risk and coordinated management may be most successful if directed at this smaller scale as a series of neighborhood-based partnerships of growers and their immediate neighbors. In fact, this appears to be where most informal communication and cooperation is already occurring. Even in this conceptual model, however, lack of success could be expected in instances where distrust and lack of shared norms exist between immediate neighbors.

Developing a disease reporting system and coordinated disease management efforts with more producers and at larger spatial extents would require different institutions. The lack of shared norms, trust, and concerns about free-riding point to the necessity to formalize structures and rules that would provide assurance (i.e., monitoring) that there is consistency in disease data collection and reporting, reciprocation, and sanctions for those who use the information for marketing purposes against other growers. Monitoring is an important component of most enduring institutions for collective action, which ensures commitment and sanctioning policies for violating agreements (Ostrom 1990). Monitoring does not necessarily need to be conducted by third parties. However, successful monitoring requires a high level of accuracy in assessing compliance, monitoring capability, reliability of sanctions, and low or no cost of administration (Ostrom 1990). These expenses of course increase the cost of implementing collective action. In addition, sufficient information must exist to impose penalties correctly in the majority of instances for such arrangements to lead to better outcomes for participating individuals. At present, these elements are not in place and are difficult for us to envision developing voluntarily at a large scale unless a substantial economic benefit from sharing this type of information could be demonstrated to the growers.

Similarly, the necessary conditions for sharing of data on best management practices also appear to be missing for information that growers view as proprietary trade secrets, such as detailed agronomic information collected on their farm. Given the heterogeneity among growers and hegemony of resources, reciprocity of information sharing would be difficult or impossible on a large scale. Certain growers simply lack the means to collect such data.

Trust was indicated as being an especially important factor for the sharing of data in the Yakima Valley and among larger operations. This could be because these growers were more likely to have a stake in a hop brokerage company, which is an avenue to establish relationships and develop trust with other growers. Furthermore, growers from large-scale operations were more likely to report competitive advantage as a barrier to the sharing of data, which may be because these operations are more likely to grow proprietary cultivars and conduct in-house research, which both require a certain degree of confidentiality and create a competitive advantage for these growers. The level and patterning of disease threat historically also varies by location, which may further affect growers' willingness to cooperate. Those in the western extent of the Willamette Valley, for instance, were more likely to indicate that the areas they farmed in were relatively free of the disease, so there was little incentive to cooperate. The data here suggest that cooperation on sharing best management practices could be conducted, perhaps, within specific networks of growers that have a shared economic incentive, such as is the case with hop broker organizations. This is equivalent to a "club" resource where nonparticipants are excluded from sharing in the resource. In this research, the

benefits of the club resource would be among growers who already possess the resources sufficient to collect, maintain, and analyze their own databases. Nonetheless, this may be insufficient in fighting a disease such as powdery mildew as a result of the need to also have alliances and coordination that are proximately situated. There is also reason to speculate that combating this threat effectively, which would require coordination that is spatially contingent, would provide a “club” resource. That is, protecting one’s crop may be seen as an economic incentive to collective action on a small, spatial scale among neighbors where relationships and trust exist.

Given the analyses presented here, we believe there is potential for collective action in disease management but with limitations on the scope and nature of the actions. Whether the factors identified here are generalizable is uncertain, although we believe they could be common in many pathosystems (Breukers et al. 2012; Milne et al. 2018). Nonetheless, this research is primarily a case study in one system, at a single time point, and in two regions, with no controlling for correlation between variables because of the observational structure of the study. We caution that the conclusions could be conflated by multiple causation of observed and omitted variables (Agrawal 2001). There is a need for empirical data from multiple systems settings to develop more broadly the theoretical basis of when collective action in pest management is likely to succeed or fail and the specific structures needed to facilitate collective action.

As a final comment, it is striking that the growers suggested ideas on how to structure an institution for disease reporting that include many of the elements that Ostrom (1990) and others theorize are essential for enduring collective action: leadership (to establish congruent rules), a committee to develop rules (an arena for collective choice), monitoring, and the need for reciprocity (expressed in terms of exclusion if individuals do not participate equally). Such conditions appear to exist, informally, among small groups of growers. These findings can support development of institutions for collective action in this and other pathosystems. The precise structure of the institutions necessary for collective action requires more engagement with stakeholders to ensure their buy-in. However, as we noted previously, we see two possible ways to organize collective action in disease management. One foundation for these institutions may be delivery of best management practices through hop brokerage companies that control distribution of their own proprietary cultivars. Formalized education efforts led by trusted growers or public sector research and extension personnel could increase information sharing on best practices within extant cooperatives. Structuring these education efforts to existing cooperatives would leverage relationships that already exist and help to build in value for participation among members. Although we find limitations to this approach depending on the openness of particular individuals and how costly data were to collect, this structure could be a beginning point for higher levels of cooperation. Second, and more informally, information sharing and perhaps coordinated pruning management between immediate neighbors appears possible in many situations. Here, establishment of standardized procedures for sampling and monitoring are needed, which might be conducted by private consultants or extension personnel who service neighboring farms to ensure consistency of data collection, reciprocity of information sharing, and leadership that can be guided by a small number of growers. Scaling up either of these efforts industry wide appears more challenging, although local, informal cooperative actions between neighbors should still improve the effectiveness of current disease management efforts, based on dispersal characteristics of the fungus. This finding may be generalizable to other plant diseases in modern agricultural systems when pathogen dispersal between neighboring farms is important for epidemic development.

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