Pathogen Incursions – Integrating Technical Expertise in a Socio-Political Context

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Limiting the movement of invasive plant pathogens into new geographic regions is one of the key planks of managing plant disease in agricultural and natural ecosystems. Disease exclusion is not an option when “[t]he whole world can be reached in a few steps” (Shaw and Pautasso 2014). Effective biosecurity measures come at a cost but provide a number of benefits, including limiting the pool of pathogens posing a threat and providing access to markets for plant products that would otherwise be closed if the invading pathogens were present (Anderson et al. 2017). Those who depend on an effective biosecurity system to maintain their livelihoods expect the system to perform and be resilient to changes in the operating environment. It is not surprising that emotions become charged when deficiencies in the biosecurity system are observed, whether perceived or real.

Here we introduce concepts for the benefit of those stepping into the maelstrom of a pathogen incursion for the first time and for a pathosystem that may be unfamiliar to them. Selected examples are drawn mainly from incursions of rust fungi (order Pucciniales) (Fig. 1) where the feasibility of disease eradication is often disputed by those potentially affected by establishment of the disease. We describe behaviors and interactions needed by scientists to engage with stakeholders to help them build knowledge that they can act upon. Biosecurity stakeholders are defined broadly as any group or individual who can affect or who is affected by the process of biosecurity. Refer to Reed and Curzon (2015) for a useful list of questions to identify stakeholders in any given biosecurity context.

In this article, topics are addressed by treating an incursion as a complex, multi-stakeholder problem, especially the role that science can play in the analysis and synthesis of real-world complexity. We begin with a commentary and conceptual framework on the complex interaction of social, political, and technical factors that may come into focus during a biosecurity response. We then review information needs and common stakeholder misunderstandings from pathogen arrival to a subsequent incursion post eradication. Finally, we explore how scientists can integrate their expert knowledge effectively into

the biosecurity system for better outcomes. This review integrates our experiential knowledge, developed through direct interactions with diverse biosecurity stakeholders.

The Technical and Political Balancing Act of Biosecurity

The incursion of a plant pathogen into a new geographic area initiates a series of expert-led decisions about appropriate risk management (Table 1). Policy options of decision-makers include: (1) eradication; (2) containment with the goal of eventual eradication; (3) containment to slow a likely transition to widespread disease establishment; (4) no containment and facilitation of long-term disease management; or (5) no intervention. The choice of policy option is based on the technical feasibility and cost-benefit of eradication, including likely impacts on crop productivity and/or ecosystem services, costs of disease management, likely restrictions and rules around market access, and other social and economic factors (Acquaye et al. 2006). While eradication is often the preferred option for many stakeholders, the few instances where a rust fungus has been eradicated have been associated with specific biophysical and social conditions (Box 1).

Biosecurity actions are informed by risk assessments that provide advice on the likely impacts of incursions (Anonymous 2010, 2020a). We define technical risk as a reductionist approach in which key biophysical parameters are known and the odds of any given event can be estimated (Wynne 1992). Scientists value assessment of technical risk because it provides clear directives on where additional biophysical information is needed. For example, van Bruggen et al. (2018) revealed uncertainties, and the significance of these, in the risk assessment of *Phomopsis vaccinii* infecting blueberries and cranberries in the European Union. Chief among these was limited quantitative data about the epidemiology of the disease. Uncertainties about key biophysical parameters, let alone uncertainties in the behaviors of people, continue to be revealed after pathogen arrival, and these can present significant challenges in science communication and risk mitigation as discussed in subsequent sections.

Historically, assessment of technical risk in a biosecurity context has not typically included the “human factor” and/or accounted for social behaviors as it has in other domains (Slovic 2000, 2016). Among the vast literature on risk and uncertainty, there is the view that ignoring uncertainties associated with human behaviors is a political process intended to deliberately bring a sense of order to a complex situation and/or to ignore a problematic set of human needs or impacts (Wynne 1992). The focus on probability as a measure of uncertainty also tends to narrow who is involved in risk assessment.

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It often assumes, for example, that decision-makers and those affected by the decisions share the same perceptions of risk, and all place the same value on the priority areas for action and/or a decision's planned outcome (Mukherjee et al. 2018). On the contrary, perceptions of risk vary among individuals and are informed by past experiences and current contexts (Mankad 2016). Quantitative risk assessment also relies on judgements that might sometimes be biased (Slovic 2000).

Eradication is a political decision. While science-based risk assessment of eradication feasibility is paramount, the decision to attempt eradication, or not, is ultimately a political one. Policy deliberations are complex because of the uncertainties and trade-offs between the costs of the eradication efforts and the expected social and economic benefits. One example is the trade-off between the cost of continued surveillance to declare "eradication" to some arbitrary level of confidence (Parnell et al. 2017), and the cost of insufficient surveillance if the invading pathogen is found to be present after eradication, including loss of confidence in the biosecurity system.

There is often a diversity in preferences among stakeholders in how the incursion should be managed (Liu and Cook 2016). There are also challenges in articulating benefits of eradication that may be unequally distributed among those incurring its costs (Liu and Cook 2016). Recommendations for plant removal, for example, may be rejected by communities concerned about the economic consequences, the environment, or loss of their deep social connection to impacted plants or flora. For review of positive and negative human responses to invasive species and the social and ecological dimensions, refer to Head (2017), Tassin and Kull (2015), and Tsouvalis (2019).

In practice, the economic and social impacts of eradication efforts are determined largely by the restrictions imposed within quarantine zones, the size of which appears to be a significant factor in eradication success (Villalta et al. 2018). Estimates of eradication costs for a

Table 1. Elements of risk management of plant diseases requiring emergency responses. Protection and preparedness prior to an incursion are of fundamental importance and can influence the effectiveness of processes to eradicate or contain an incursion.

Element	Purpose
Emergency preparedness preincursion	• Preemptive breeding for disease resistance • Risk assessment simulations and scenarios • Education and awareness • Preparation for timely detection, rapid and coordinated responses • Formation of partnerships for joint actions • Development of a communications strategy • Testing communications networks
Surveillance	• Timely detection of an incursion • Estimation of the nature and extent of the problem • Implementation of control once infected site identified
Domestic quarantine	• Minimizing spread
Pre- and postharvest disease management	• Minimizing and reducing the rate of spread • Maintaining market access

Fig. 1. Examples of two rusts referred to in this article: **a**, patches of European blackberry (*Rubus fruticosus* L.) with different severities of leaf rust caused by *Phragmidium violaceum*; **b**, scanning electron micrograph of urediniospores of *Austropuccinia psidii* (myrtle rust), courtesy L. Morin, CSIRO; **c**, uredinia of *P. violaceum* on European blackberry, from Morin and Evans (2012); **d**, uredinia of *A. psidii* on *Agonis flexuosa* 'Afterdark,' courtesy L. Morin; **e**, telia of *P. violaceum* on European blackberry.

BOX 1

Eradication of exotic rusts

The Global Eradication and Response Database (GERDA) (Kean et al. 2020) presents only two examples where an exotic rust pathogen (order Pucciniales) has been eradicated in Australia and New Zealand, with few examples elsewhere. The eradications in Australia and New Zealand were (1) *Phakopsora euvitis*, cause of grapevine leaf rust, first found on a *Vitis* sp. in a home garden in Darwin in northern Australia (Weinert et al. 2003); and (2) *Puccinia cygnorum*, found on *Astartea fascicularis* (Myrtaceae) in the Napier Botanic Gardens in New Zealand (Dick and Inglis 2011).

Eradication of grapevine leaf rust, described by Villalta et al. (2018), involved many infected plants; however, these were destroyed across a large quarantine area after an intensive community awareness, education, and surveillance program. Moreover, these infections were >1,000 km, and mostly >3,000 km, from commercial plantings of table and wine grapes in central and/or southern Australia.

In the New Zealand case study, only two plants infected with *A. fascicularis* were found. Trace-back revealed that they had been bought from a local nursery, with the nursery industry importing cuttings for the cut flower industry in New Zealand. Similarly, eradications of rusts on gladiolus and chrysanthemum have involved infections of small numbers of plants in home gardens, protected cropping (e.g., glasshouses), nurseries, or small areas of open field production (Kean et al. 2020).

Based on the contexts and conditions in the above examples, eradication of a rust pathogen may be technically feasible when (1) disease symptoms are limited in distribution and detected soon after an introduction; (2) the source of the disease outbreak can be traced back to a known and localized source (e.g., infected plant material imported recently to the region), which in turn can be traced forward to other potentially infected sites; (3) the affected sites are readily accessible; (4) few uredinia and urediniospores are observed at the affected site; and/or (5) detection occurs at a time of year when conditions are suboptimal for pathogen infection and reproduction.

plant-based industry prior to an incursion will vary depending on the different scenarios envisaged: these include the cost of response actions (e.g., domestic quarantine), owner reimbursement costs, and grower cost and revenue changes (Cook et al. 2016).

Balancing interests can cause delays. Time-dependent decisions may be delayed while regulators and governments balance the agendas and vested interests of multiple stakeholders. Specific actors may advocate vigorously to serve their own goals without due consideration of the overall or long-term benefits for the given jurisdiction (Ostrom 1998). Incomplete, erroneous, and/or selective information may be used to support a particular position on how an incursion should be managed; that is, scientific results may be politicized (Allenby and Sarewitz 2011; Sarewitz 2004). Moreover, emotions can intensify when coalitions or breakaway groups of crop producers or industry segments form to advocate a particular position, or to bring issues back to the negotiating table, when decision making by regulators does not serve their particular expectations (McAllister et al. 2017) (Box 2).

All stakeholders, including scientists, need to consider that any delay in decision making caused by regulators waiting for science-based answers may result in a worse outcome than pursuing a “best bet” strategy. Increased likelihood of poor outcomes are especially true for rust fungi because of the nature of aerial dispersal of urediniospores (Brown and Hovmøller 2002; Severns et al. 2019). When the “best bet” decision is containment rather than eradication, then rigorous containment protocols to slow the rate of pathogen spread may increase the time available to develop long-term disease management responses that are effective in the local environment (see example in Box 2). When the “best bet” decision is to pursue long-term disease management, the option to conduct research within the affected jurisdiction under local production conditions becomes feasible. An example is the transition to management program for myrtle rust in Australia from 2011–2013 to assist primary industries to manage this disease (Anonymous 2011; Carnegie and Cooper 2011; Carnegie and Pegg 2018). In this scenario, research and extension activities can be targeted to help landholders and primary producers identify responses that provide flexibility in the face of ongoing uncertainty.

Over time, an infected premise (IP) or area of land subjected to concerted disease management may be granted property- or area-freedom status if there have been no new disease detections after a minimum period of surveillance (see Anonymous 2019a) for a case study of banana freckle caused by *Phyllosticta cavendishii*. Meanwhile, new IPs or infected areas may be declared, such as new detections of grapevine leaf rust (*Phakopsora euvitis*) in 2006 in the

Northern Territory, Australia, following an eradication program (Anonymous 2015). If new IPs are occurring at a rate that is higher than those being declared disease free, then questions may be asked about the tipping point at which the pathogen can no longer be contained. To answer this question, decision-makers must review their risk assessments and decide when it is no longer technically feasible or cost beneficial to contain the disease.

Disputes are common. Myrtle rust (Carnegie and Pegg 2018) (Fig. 1) and blueberry rust (Box 2) are examples from Australia that illustrate the types of disputes that can arise among stakeholders during an incursion, even among scientists who may hold different perspectives. Different taxonomic concepts and assumptions, for example, can have important implications for biosecurity containment and monitoring efforts. Pathogen identification can alter predictions of rate and extent of spread and impacts in the introduced range (Elith et al. 2013). Decision making can be delayed when pathogen identity cannot be established quickly, or if the initial determination is later contested in a way that clouds decision making around eradication (McAllister et al. 2017). Decisions on the taxonomic concept to pursue may also be perceived to have political intent, as suggested by Carnegie and Pegg (2018) in relation to the myrtle rust incursion in Australia.

Intermediaries can spend inordinate amounts of time on dispute or conflict resolution of the type that can cause delays during time-critical operations. Individual intermediaries may themselves be overtly political when they deliberately work with certain stakeholder groups to help them achieve a particular goal (McAllister et al. 2017). As various conversations are translated, conflated, or misrepresented through social networks, concerned individuals may make decisions that potentially harm the greater biosecurity objective; for example, the farmer who does not declare a detection because of the perceived social and economic impact (Mankad et al. 2017).

We observed a loss of trust among biosecurity stakeholders after detection of the blueberry rust pathogen in the Australian state of Tasmania (Box 2). As the situation unfolded, cries for more and improved communication from the biosecurity authority about rust eradication efforts become louder, with some in industry claiming they were being kept in the dark deliberately (Anonymous 2017). Meanwhile, the public sector agency governing the biosecurity authority reviewed communications from our institute about plans for research on blueberry rust. The advice was to de-emphasize reference to long-term disease management in the research proposal because the agency felt that their constituents, who were advocating for disease eradication, were not yet ready to acknowledge the worst-case scenario. It was also implied that constituents might perceive

BOX 2

Balancing multiple interests: the case of blueberry rust in Tasmania.

At the time of writing, regulators in the Australian state of Tasmania have set the goal of containing rather than eradicating blueberry rust caused by *Thekopsora minima* (Anonymous 2019b). After three infected properties were identified in 2016, a coalition of blueberry growers from small to medium-sized businesses felt their interests were not being served by the existing peak industry body. They perceived that a larger, corporate-style producer had undue influence in presenting an alternative view about the significance of the blueberry rust incursion (Anonymous 2017). This large producer has operations in other Australian states where blueberry rust has been present since 2001. The coalition of smaller growers harnessed an alternative industry body to advocate for the eradication of blueberry rust. Their vocal calls for action contributed to the establishment of a parliamentary inquiry around the biosecurity process in Tasmania (Anonymous 2017). This case illustrates that blueberry growers in Tasmania at that time had struggled to achieve a united position or broad acceptance of the decision to contain rather than eradicate blueberry rust, or to build capacity to prepare for future threats. The challenge for conducting science in this context is that there are potentially multiple target audiences with diverse needs and goals that ultimately need to be aligned with the prevailing biosecurity policy. It is also in this context that communication between scientists and industry can become constrained, which limits full understanding of motives and potential ways forward.

the research as an admission of failure in the biosecurity process when in fact the intent was to prepare for a situation where eradication seemed increasingly unlikely. Given this context, messaging from scientists must be consistent with the current policy environment to maintain trust in the biosecurity system. Trust, as defined by Ostrom (1998), is a core and central concept in collective action because of the way it affects the behaviors of those involved.

As an incursion progresses, and knowledge of disease spread and impact emerge, so too does hindsight bias where people believe they knew the outcome before it happened (Roese and Vohs 2012). Certain outcomes may simply consolidate the views of stakeholders who see events, in hindsight, as more predictable than what was foreseen. “Everyone is an expert in hindsight!” is an expression sometimes uttered by decision makers when venting their frustration. The decision maker’s dilemma in relation to how individuals perceive information at any given point in space or time was articulated well by Florec et al. (2013), who said that “What you know, when you know it, and for which spatial point is critical.”

Conceptual framework for a complex problem. Here we describe a conceptual framework for the entire biosecurity system to aid understanding of the social, political, and biophysical factors that shape an effective postincursion response. The biosecurity system contains three non-mutually exclusive phases: (1) preincursion, (2) postincursion, and (3) recovery (Fig. 2). Each phase has several elements that can be conceived as “action situations” in which people are interacting in different ways and often collectively (Berkes and Folke 1998; Ostrom 1990). These action situations may be relevant to one or multiple phases. For example, risk mitigation is conducted during the preincursion phase, while knowledge, skills, and tools can be developed and/or enhanced within the preincursion and postincursion phases.

The outcomes for each action situation (Fig. 2) contribute to the overall effectiveness of the biosecurity system. High-level outcomes include rapid recovery of affected enterprises and communities when management responses are in a relatively stable state, and preparedness for the next incursion. The desired state is a resilient system that implies a community that is adaptable, able to function under stress, understands risks, and are empowered to act individually and collectively (Maclean et al. 2014; Walker et al. 2004). The term also implies the potential of a community to bounce back to some “normal” condition after a disturbance and, in some contexts, the ability to recover at all (Walker and Salt 2006). Some authors also emphasize that resilience is the opportunity that a “shock” creates for innovation and development (Folke 2006).

Each action situation in the biosecurity system will be shaped by key contextual factors. These include: (1) the underlying biophysical conditions; (2) the rules in use, which are not necessarily the written, formal rules; and (3) the most relevant attributes of the community, especially levels of trust and shared norms of reciprocity (Ostrom 1998, 2011). Integral to decision making are the key stakeholders who have critical differences among them in how they articulate

the problem to be solved (Fig. 3). Variation in perceived gains from cooperation relative to the need of individuals or organizations to maximize their own goals will affect the interplay of stakeholders involved in a biosecurity response. A social dilemma occurs when stakeholders are left in a worse state when there could have been more productive cooperation and outcomes to avert disaster (Ostrom 1998).

Assuming successful biosecurity requires effective collective action; we adopt the concept of Sherman et al. (2019) that a pathogen that moves unimpeded across a landscape can be considered as “negative common property.” Common property typically describes resources where one person’s consumption is subtractive from the total resources; for example, water used for irrigation (Ostrom 1990, 2010). In the study of Sherman et al. (2019), removal of flag shoots of powdery mildew of hop was conceived as a “resource” subtractable from the common pool of inoculum. Similarly, rusts are dispersed by airborne spores across farm boundaries. Thus, actions to remove the resource from the common pool are beneficial for all stakeholders rather than detrimental. The question then becomes how to identify, understand, and analyze the critical formal and informal relationships among the elements of the biosecurity system that govern the outcomes for the common property, including the role of the technical expert within the system. Colding and Barthel (2019), for example, situate ecological (epidemiological) knowledge and understanding as a critical link to, and embedded within, adaptive management practices and the institutions that influence the actions and behaviors of people.

The notion of biosecurity as a social-ecological system (Ratzlaff 1970) with multiple tiers and variables for each “action situation” is helpful because it has been applied in a wide set of fields and practices involving common property (Colding and Barthel 2019; Hinkel et al. 2014; Kiser and Ostrom 1982; Ostrom 2005, 2011). If the biosecurity system is conceived and analyzed as a social-ecological system, then responding to a pathogen incursion is clearly a complex problem, considered by Campbell et al. (2015) to be “characterised by technical complexity and often uncertainty, large scales in space and time, a mix of social, economic and biophysical drivers, abundant but disparate and heterogeneous data, and contested issues among diverse stakeholders.” It is in this context that scientists and their host institutions must consider deeply their role and approach when stepping in to support decision making. At the very least, a scientist must have knowledge of the national biosecurity system, the process for risk assessment, and established communication pathways (see Figure 1 in McAllister 2015). From there, understanding of the motivations, drivers, and goals for key decision-makers and the scale at which they are operating helps all stakeholders to structure the problem to be solved and identify high priority knowledge gaps (Garrette et al. 2018).

In the following sections, we move beyond the notion that scientists function solely to generate knowledge but are an integral component of “knowledge flows,” including: (1) interpretation and translation; (2) knowledge exchanges or mobilization (Young et al. 2016); and (3)

co-learning and co-production of knowledge (Wyborn et al. 2019) (Table 2). How knowledge is shared and cocreated with stakeholders during a biosecurity incursion is critical not only to an effective response but also to adaptive capacity and long-term system resilience (Folke et al. 2010).

Information Needs and Common Misunderstandings

During the early stages of a response, questions requiring science-based information can build up faster than answers. Stakeholders tend to pose similar questions from one biosecurity case to the next (Table 3). Receptivity to new or existing information is often greatest when it is supplied at key stages during decision making. However, the situation is complicated by the capacity and willingness of different stakeholders to absorb, comprehend, and act upon information provided (Mankad 2016).

Scientists who become involved during an incursion can benefit greatly from those who have already identified, contextualized, and prioritized knowledge needs and gaps. Even so, new information, new contexts, and even new means or tools will emerge that require agility and flexibility in knowledge generation and sharing as a potential crisis unfolds (Magarey et al. 2009). The following sections address key elements of pathogen biology and disease epidemiology for consideration in biosecurity responses. They also highlight where limited understanding or application of often incomplete, science-based information can lead to unrealistic expectations of the biosecurity system, frontline operators, and/or landowners.

Pathogen Arrival. Scientists need to be mindful of what their audience are likely to understand when a pathogen or disease symptoms are first detected. The interaction of pathogen, host, and environment required for disease to occur—the “disease triangle”—is an abstract concept beyond the comprehension of some stakeholders. Stakeholders do not necessarily understand that “disease” and “pathogen” are separate concepts, nor that pathogen detection does not necessarily equate with the presence of disease symptoms. It is therefore not surprising that some stakeholders may not comprehend that the first detection of visible disease may not be synonymous with the location

of the very first infection. Indeed, it is often unclear when and where a pathogen has entered a region.

A negative consequence of low understanding of concepts in plant pathology is that a landowner may feel ostracized when their local community assumes, rightly or wrongly, that they are responsible for the first observed disease outbreak. The concept of “latent infection” may also be obscure to those that assume removal of symptomatic plant tissues equates to removing the pathogen. To convey meaning and build understanding of a scientific concept, it can help to evoke real-world situations focused around individuals and their beliefs, emotions, and intentions (Zdrzilova et al. 2018).

Scientists are often subjected to ongoing questions about why a disease cannot be eradicated. Consider the situation where a scientist has been invited to give a presentation to primary producers to inform them about the new disease threat. A farmer in the audience fearing consequences to their livelihood might ask the presenter, “Is this rust going to be a problem or not?” The scientist might then respond by exclaiming “It depends!”, a signal that flags their understanding of statistical probability and the multiple variables involved. In contrast, the way the audience perceives risk may have multiple dimensions (Slovic 2000, 2016); for example, the way someone imagines the negative consequence of a disease outbreak may feel as worrying when its probability is low as when it is high (Slovic 2016). To quote Shaw and Pautasso (2014): “Arguments are much simpler when phrased deterministically, so there is extra labor in taking account of uncertainty.”

After an incursion, stakeholders may claim that publicly funded surveillance is under-resourced; however, even the best biosecurity controls to minimize risk cannot prevent all new arrivals. Viable spores, particularly those of rust fungi, may arrive on external surfaces such as human clothing, airline baggage, or shipping containers and their contents (Holliday et al. [2013] and references cited therein). A traveler arriving in Australia by air from Europe was the likely pathway of entry of *Puccinia striiformis* f. sp. *tritici* prior to the first detection of yellow rust on wheat in 1979 (Wellings 2007). Hodson (2011) also describes the dramatic consequences of

Fig. 2. The biosecurity system comprises a series of “action situations” (outer ring) and outcomes (boxes) associated with each of three phases (inner ring): preincursion, postincursion, and recovery. The latter refers to the postincursion period when responses are in a relatively stable state before the next threat arises. This schematic representation does not necessarily imply that the biosecurity phases and “action situations” are ordered in time, as in practice they may overlap or reiterate along a continuum. Effective knowledge flows for any given “action situation” help to build resilient communities that are adaptable, able to function under stress, understand risks and are empowered to act.

In addition to human-mediated transport, fungal pathogens can also spread to new regions through long-distance, single-step transport of spores by air. For example, urediniospores of *Phakopsora pachyrhizi*, the cause of Asian soybean rust, mostly likely arrived in the United States from Colombia over a period of 9 to 12 days in association with Hurricane Ivan in 2004 (Isard et al. 2006). Similarly, sugarcane rust was almost certainly introduced into the Dominican Republic from West Africa by cyclonic winds in early June 1978 (Purdy et al. 1985). More recently, tropical cyclone Debbie has been associated, albeit inconclusively, with the arrival of *Austropuccinia psidii* (myrtle rust) on the Kermadec Islands north of New Zealand in 2017 (Makinson 2018).

Host-pathogen compatibility is another key factor affecting pathogen establishment. In work to identify potential agents for the

The examples above of human-mediated or air transport of invading pathogens or biotypes with varying disease potential highlights the complexities of communicating to nonscientists potential entry pathways and associated uncertainties. Broad comprehension of any target audience depends on applying adult learning principles such as presenting the same information in different ways (Fleming and Mills 1992). How information is interpreted by individuals is another matter and is often beyond the control of the messenger. An important area of interdisciplinary research relevant to biosecurity is the communication of uncertainty about facts, numbers, and science and the way it affects trust and decision making. van der Bles et al. (2019) combine a statistical and psychological perspective in their review of this topic.

Surveillance for several growing seasons may be required to increase confidence of eradication of disease to the level required by

the biosecurity regulator and/or the export destinations for plant products. Scientists can facilitate this work by contributing knowledge about pathogen life cycle, distribution of potential host plants, conducive environmental conditions, and suitable detection technologies (IPPC 1998). Even so, it is generally impossible to verify total eradication of an invading pathogen because surveillance necessarily involves sampling rather than monitoring every available host plant. If no disease is found within any given sampling area, then the disease may have been missed by chance. Thus, there may be some residual infection to re-establish the disease in the future. Hosts in inaccessible locations, and/or the height, density, and/or aspect of foliage can also hinder effective monitoring of plants sampled for inspection. For example, *Tsuga* sp. has been reported as an alternate host for *Thekopsora minima* (Sato et al. 1993), the cause of blueberry rust. The height of these conifers can exceed 20 m (Daley et al. 2008), thus potentially hindering detection of the aecial spore state.

If disease is detected after eradication and multiseason surveillance, then the series of questions posed by stakeholders during the initial incursion are likely to resurface and may be compounded by a series of founded or unfounded accusations regarding the rigor of the biosecurity system. A stakeholder can lose trust in biosecurity operations if a disease reappears after eradication, regardless of whether it is a new incursion or an eradication failure. Affected stakeholders who contribute actively to a formal surveillance program are likely to develop an understanding of the process and its purpose, and hence its limitations.

Disease Spread. Rate and direction of an invasive pathogen's spread are dependent upon multiple factors. Key among these are the climatic conditions, distribution of suitable hosts, and the availability of susceptible host tissues at the time of incursions and subsequently. Knowledge of pathogen hosts and/or their spatial distribution may be incomplete. While preincursion risk modeling can provide indications of spread, accuracy of model outputs is dependent upon the parameters considered and the validity of data upon which predictions are made. Peculiar interactions between pathogen genotype and the local environment cannot be modeled or foreseen during risk assessment. Kriticos et al. (2013), for example, acknowledge that models for the potential distribution of *Austropuccinia psidii* in Australia "were either based on empirical biological knowledge of the organism's response to environmental variables, or its known distribution, but not both, and therefore may be sub-optimal."

Preincursion estimates of the climate niche required for pathogen survival and spread may not account for microclimates created by crop cultural techniques or land variability that either promote or suppress local disease development (Berthon et al. 2018). Surveys of myrtle rust 2 months after being discovered in Australia indicated that the rust was not spreading as quickly as anticipated during the cooler months (Carnegie and Cooper 2011). Six months later, with warmer spring and summer conditions, airborne spores had become plentiful and spread was faster.

Variation in the rate of leaf emergence among plant hosts in any given environment, as observed for taxa of European blackberry (Evans et al. 2011), is likely to affect disease severities observed.

The density of uredinia on leaves of a single shoot of a perennial, woody host after inoculation with a rust pathogen is known to vary with leaf position or leaf age (Anthony et al. 1985; Coutinho et al.

Table 3. Common questions directed to plant pathologists and related professionals during an incursion of a pathogen, especially in public forums where stakeholders are seeking immediate answers

Upon detection

What will be the impact of the disease on the crop if no action is taken?
Can the pathogen be managed if not eradicated and at what cost?
Can the pathogen be eradicated at the initial site(s) where it has been detected?
What other host plants could be infected and where are they?
How did the pathogen get here? Who is responsible?
Will the pathogen survive the winter or the summer? If so, under what circumstances?
If the disease is eradicated, how long will it take until there is another incursion?
If the disease is contained, what actions could be taken to increase the chance of eradication in due course?

Related questions:

Is a risk assessment available? Is the risk assessment relevant and useful for this region?
Do different plant varieties vary in their disease susceptibility?
Is the disease more severe in different types of production systems?
How many plants are infected, and where are they?
What measures would indicate the pathogen has been eradicated?
Where can the pathogen spread to next?
Where did the pathogen come from? How far do spores travel and how?
Has there been one or more entry pathway?
Is there more than one pathogen biotype?
How do primary producers in other regions, where the pathogen is established, manage the disease?
How relevant are the disease management strategies in other regions relevant to the current production context(s)?
Are those management options available to producers in this region?
Will those management options work given the environmental conditions in this region?

Spread, persistence and new incursions

How did the pathogen arrive at new, secondary locations?
Can the pathogen be eradicated at these secondary sites of detection?
How will the pathogen spread to other locations, and how far?
What is the tipping point at which the disease can no longer be contained?
Is the reappearance of the disease after eradication a new incursion or the consequence of eradication failure?
Related questions:
How far do spores travel and how? How are people contributing to the spread of the pathogen?
Is infected plant material being transported within the region?
Will infected plant material transfer the pathogen to healthy plants?

Table 2. Types of knowledge flows to support a biosecurity response and examples of their purpose

Interpretation and translation	Knowledge exchanges	Colearning and coproduction of knowledge
To explain a scientific or complex concept for ease of understanding in a given context	To facilitate demand or issue articulation and identify leverage points	To reveal and integrate different forms of knowledge to create new ways of knowing
To connect the content of knowledge to its value or utility	To reveal opportunities and develop a common departure point for collective action	To accelerate production and adoption of new solutions
To provide expert advice or to counsel on issues affecting groups or individuals	To improve relations and understanding among diverse actors; to manage expectations	To develop ongoing learning experiences in a continual design-evaluation cycle
To raise or provide situational awareness	To generate unexpected feedback and/or sudden realization about a current situation	To enable evolution, revision, adaptation, and advances in knowledge
To test scenarios or predict, project, or explore future outcomes	To make assessments which have the potential to impact on current and future decision making	

1994; Evans and Bruzzese 2003; Evans et al. 2011; Sharma et al. 1980). If the rate of leaf emergence for any given plant biotype in the field slows markedly as a result of environmental stress, then presumably the proportion of young leaves on a shoot that are highly susceptible to infection by a biotrophic pathogen declines (Merry et al. 2013). Even so, inoculum from few or many uredinia are likely to spread on susceptible hosts over increasingly greater distances under favorable environmental conditions (Severns et al. 2019).

Modeling studies of wheat stripe rust from inoculations of experimental field plots demonstrated that initial disease severity within a defined focal area determined the decline in severity with distance from the source (Severns et al. 2019). Higher numbers of uredinia within the focal area led to a wider area of spread; however, all disease gradients had long tails and were characterized by an increasing velocity of spread at the epidemic front. Severns et al. (2019) concluded that disease eradication is likely to be difficult unless conducted soon after an epidemic is initiated. Treating all host plants within an initial area to prevent spread of a rust disease may be futile if the timing of disease control is too late.

Differences in agricultural and noncultivated ecosystems need to be accounted for when projecting the rapidity of disease spread. Unlike genetically uniform monocultures, the distribution of susceptible plant hosts in natural ecosystems may resemble linear corridors (e.g., along roadsides and in riparian zones), discontinuous patches (e.g., weeds invading farmland), or continuous, blanket growth occupying vast areas such as entire valleys. Heterogeneity in environmental conditions and host quality, characterized by a genetically variable host and/or variation in plant tissue susceptibility, may limit the establishment of a pathogen biotype arriving by air to a new location within the introduced range (Burdon et al. 1996; Gomez et al. 2008). Even if there is a compatible host-pathogen interaction in a new location, a pathogen biotype may arrive too late in the growing season to establish disease and produce inoculum for subsequent spread (Burdon et al. 1996).

European blackberry (*Rubus fruticosus* agg.), an aggregate of closely related taxa, demonstrates the potential for fine-scale variation in susceptibility to disease caused by *Phragmidium violaceum* in climates conducive to this rust. *P. violaceum* was first reported in Australia in 1984 following an unauthorized introduction (Marks et al. 1984). The first author has observed patches of European blackberry with trace amounts of rust disease adjacent to patches with severe disease (Fig. 1a). One hypothesis is that the local population of *P. violaceum* lacked genotypes needed for a compatible interaction with all patches of blackberry present at the site. Studies revealing that historical populations of *P. violaceum* in Australia were genetically differentiated (Gomez et al. 2008) and that isolates varied in pathogenicity (Evans et al. 2011) support this hypothesis. Disease spread is therefore likely to be influenced by “patchiness” in the host-pathogen interaction.

Likely Impacts. Stakeholders, especially commercial entities and those facilitating access to markets, usually want to know immediately the likely consequence of introduction if the disease is not eradicated. Market access rules dictate the degree of disease control expected and the process by which management is undertaken, and hence cost. There may also be flow-on effects impacting compliance to environmental or organic accreditation schemes if farmers need to start spraying nonaccepted synthetic pesticides in order to comply with containment protocols.

The likely biophysical impact of a plant disease at the landscape scale depends on whether the disease is likely to be confined to commercial plant production (of varying scale and distribution) or will propagate through the broader ecosystem. In the absence of credible evidence, stakeholders tend to assume the worst-case scenario. Initial fears of a sudden and widespread threat often subside with time when it becomes evident that crop yields, for example, are within the boundaries of interannual variation and/or crop yield is low for other reasons. Coffee rust, caused by *Hemileia vastatrix*, presents an interesting case study where disease exacerbates differences in yield among seasons (Avelino et al. 2015; Cerda et al. 2017).

In noncultivated ecosystems, it may take a decade or more for significant impact of a plant disease to become visible, as was the case

with *Phragmidium violaceum*, a rust fungus infecting weedy European blackberry in Victoria, Australia (Bruzzese and Lane 1996; Mahr and Bruzzese 1998). An introduced pathogen might also interact with local biotic and abiotic factors to cause a decline syndrome in some local populations of the host plant but not others (Aghighi et al. 2014).

Models to assess impacts nationally often do not provide the granularity or resolution that accounts for variation in climate and/or the different production or marketing contexts facing individual producers or local economies. Coffee rust epidemics in Central America, for example, have often been most severe when coffee prices were low because optimal disease management practices became unaffordable when profitability was reduced (Avelino et al. 2015). Ultimately, the availability of cost-effective and practical options for crop protection will dictate within- and among-season variation in disease severity.

Open to question is whether an immigrant pathogen biotype or strain has similar environmental requirements for infection or other life-cycle processes to those used to calibrate preincursion risk models. *Puccinia striiformis* f. sp. *tritici*, the cause of yellow rust of wheat, is causing epidemics in warmer areas where the disease was previously considered unimportant or absent (Hovmøller et al. 2010, 2011; Johnson 1984). This rust fungus provides examples of variation in thermal tolerance among strains or isolates as evidenced by variation in infection efficiencies at different temperatures (de Vallavieille-Pope et al. 2018; Mboup et al. 2012). However, the predominant strains in any given location depend not only on thermal tolerance but also the wheat varieties present and corresponding pathogen virulences.

Investigating how disease develops in landscapes at various scales in time and space, and hence its impacts, remains an ongoing challenge. Postincursion modeling, like preincursion risk models, can suffer from a lack of quantitative epidemiological data and technology to collect such data, inaccessible private or proprietary data on plant movements, and aggregated data of insufficient resolution such as those maintained by public agencies about product imports, exports, or the value of agricultural production. Tools such as Global Navigation Satellite System (including GPS), Geographic Information Systems, and various remote-sensing platforms, present both opportunities and challenges in understanding spatio-temporal variation in plant disease (Mahlein et al. 2018). Key challenges are a lack of empirical validation of sensor data that serve as proxy measures of biological information, and the need to optimize resolution (Hernández-Clemente et al. 2019). With further research, these tools along with new and emerging information and communication technologies are likely to play an increasing and significant role in providing greater spatio-temporal completeness of disease-related data in a region of concern.

Involving Stakeholders for Better Outcomes

Stakeholder involvement can potentially lead to a richer set of approaches to risk assessment (Gilmour et al. 2011) and/or how uncertainty or bias is reduced, accepted, or embraced. Such processes can create scenarios, aid discussion of potential outcomes, and produce outputs relevant to the different contexts (McRoberts et al. 2003, 2011; Shepherd et al. 2006). Scenarios may vary from those that maximize the odds of pathogen eradication to those that minimize the costs of biosecurity actions. Effective intermediaries or facilitators will work with stakeholders to reveal the diversity of values, aspirations, and goals to each other. The scenario that can be supported by a broad range of stakeholders can then be identified, a process which may be facilitated by explicit articulation of how uncertainty is incorporated into risk models (Kusunose and Mahmood 2016). Discussions with affected stakeholders can then focus on those instances where outrage about biosecurity decisions or management actions is misplaced because the technical risk is genuinely small.

Building a network among stakeholders of so-called “biosecurity champions” prior to an incursion can help form a well-prepared early response team to advocate and support science-based messaging on biosecurity (Mankad et al. 2017). Farmers who have had a direct

experience of an incursion with deep social and financial impact can facilitate effective peer-to-peer learning. These advocates for best-practice biosecurity can provide those in other sectors with some beacons of hope, especially if the lessons learned have translated over time to greater land productivity, profitability, and business sustainability (see the story of Templeton Farming Enterprises in Australian Government 2020). Participation in preborder testing of scenarios can also place potential advocates “psychologically closer to incursion events” (Cook et al. 2016), thus improving their potential to convey the gravity of unwanted futures. The plant pathologist arriving fresh on the scene during an incursion is likely to have a much easier task in communicating new information if knowledge has already been cocreated using this participatory approach.

In practice, most forums for decision making at the start of an incursion are typically constrained to a few stakeholders as specified by lead agency processes. This initial situation can create a form of information asymmetry in which a few experts persuade other experts and nonexperts. Nonexperts may have little influence on decision making or may feel pressured to accept a group decision despite the intention of an inclusive process. Narrowing diversity of thought in decision-making forums can have negative consequences for some groups of stakeholders, through limiting the scope and types of knowledge available and inattention to hidden biases (Bang and Frith 2017; Kirman et al. 2019). In the case of the incursion of myrtle rust in Australia, new participants joining the response in later stages introduced new thinking that highlighted that environmental costs had been underestimated in initial cost-benefit analysis (McAllister et al. 2017).

Liu et al. (2012) provide a generalized framework to facilitate participatory decision making in the management of biosecurity responses (see also Liu and Cook 2016). This framework appears to build on those developed for decision making to solve complex environmental issues. A scientist operating within this framework will share their views and technical knowledge concurrently with other participants such as response managers. A formal and structured process reveals differences in opinions and shows how social and economic conditions valued by stakeholders should be articulated and incorporated across multiple objectives of the biosecurity response. Conflicts are resolved through explicit trade-offs to achieve the outcomes stakeholders want. In related work, Mukherjee et al. (2018) compare six techniques derived from the social sciences to elicit the views and judgements of stakeholders, including experts, at various stages of decision making for biodiversity and conservation management. These contributions highlight the opportunities to bridge disciplinary boundaries to support effective exchanges of knowledge and real-world decision making.

Trust in information being communicated more generally depends on the strength of personal relationships within the system (Ostrom 1998). Ideally, activities designed to build trust, understanding, and clear accountabilities among stakeholders will have been initiated well before an incursion, forming an integral part of preborder preparedness. McAllister et al. (2017) compared and contrasted collaboration and coordination in the context of pest and disease incursions. Collaboration was found to be the slower and more expensive task. Once trust and relationships are established, coordination of largely technical capacities can proceed with lower transaction costs. Participants must then work actively to maintain trust throughout the post-incursion period. Staff turnover in agencies responsible for biosecurity policy and operations may present an additional risk when tacit knowledge, intellectual capital, productive relationships, or training skills are lost from the system.

Participatory processes are intended to generate a more informed and transparent biosecurity response that also communicates the profound uncertainties. While grounded in sound “systems” theory, they also present some key challenges (Wyborn et al. 2019), including who should be chosen to participate and when, and the transaction costs associated with collaboration. Each actor must perceive value in participation, and above all are appropriate governance structures and facilitative leadership that can harness diversity of thought and minimize groupthink (Hart 1991) and functional stupidity (Alvesson and Spicer 2016).

Role of the plant pathologist. We argue that scientists need to move beyond the stereotype of the distant subject-matter expert or a “servant” providing independent scientific advice (Martin et al. 2012; Mukherjee et al. 2018). Scientists contributing expertise in plant pathology are one of many contributing disciplines, along with social research (e.g., Maclean et al. 2018), that inform how best to support farmers and landholders during each phase along the biosecurity continuum. All need to be aware of the industry or land management context and potential deficiencies in system preparedness and other complexities as they rapidly build and share their knowledge base.

The blindness of scientists to the perspectives of those implementing response actions and those impacted by it was instrumental to the failure to eradicate medfly in California in the early 1980s (Lorraine 1991). A key area of uncertainty that was overlooked, for example, was variability in human behavior in responding to instructions of biosecurity managers. This variability stemmed from individual perspectives or biases on how the problem should be treated, and/or inability to translate technical specifications into practice. Social science and/or stakeholder analysis can at least aid understanding of the attributes of those who will use, or be influenced by, the information provided from a risk assessment and/or to inform proactive biosecurity actions (Head 2017; Mankad 2016; Young et al. 2016). Such awareness shapes what new or existing knowledge is introduced to the system, and when and how a knowledge exchange will occur for maximum effectiveness.

Involvement in problem structuring through facilitated group work can help scientists test their assumptions, and through interdisciplinary research, identify actions that will be socially or economically acceptable. For example, an assumption that stakeholders will protest removal of infected trees may be unfounded in the absence of qualitative social data and/or community engagement to facilitate frank conversations about risk, and colearning to identify acceptable management options. Scientists must also check continuously for and prioritize new issues or opportunities that arise during the process. Ideally, change and continual improvement is facilitated through periods of reflection to evaluate early or intermediate outcomes that inform how to proceed with the next steps (Meinke et al. 2009).

Scientists must develop the confidence to share incomplete knowledge and results early and regularly because feedback from stakeholders can shape next activities and identify new questions. In our own extension practice, we receive feedback regularly from farmers and landowners that they want to hear directly from researchers when new knowledge becomes available. Even so, effective communication of information influencing decisions on disease management depend on trust in those giving advice (Sherman and Gent 2014). In a study of hop and mint farmers in Washington and Oregon, Sherman and Gent (2014) provide compelling evidence that farmers are more open to arguments that respect their experiential knowledge and take into consideration their production goals and constraints. Technical experts in this context have a responsibility to display empathy and to become effective science communicators through practice. The challenge is that it takes time to develop relationships of the type that build trust and increase receptivity to information. Sources of trusted information in the study of Sherman and Gent (2014) were those with whom a long-term relationship had been established and were known by the farmer to be knowledgeable and effective in addressing their needs.

A key skill required by scientists operating in a biosecurity context is the ability to respond confidently to questions around a decision not to eradicate a disease. Technical experts are likely to provide answers according to the science; however, what is said and what is heard by primary producers may be different things. These stakeholders may perceive a technical response to be biosecurity policy unless the scientist states explicitly that their communication is about the science. To field questions effectively, it is imperative that scientists (1) understand a given stakeholder’s perspective on the problem; and (2) facilitate integration of new knowledge with existing knowledge by understanding the common scripts of the target audience

(Vanclay 2004; Vanclay and Enticott 2011). Even when complete information is translated well, it may be perceived as irrelevant, misguided, false, or having no value in addressing the issue at hand (Bennett and Jessani 2011; Cash et al. 2003; Evans et al. 2017). The latter can arise when people interpret information according to their pre-existing beliefs; when we hear something that is consistent with what we believe, then we are prone to believing it is true. Conversely, when we encounter information that conflicts with our beliefs, we are more likely to discredit the source (Kahan et al. 2011).

After generating or sourcing new information during an incursion, pathologists typically communicate findings in a “top-down” manner via fact sheets or formal presentations to stakeholders. This approach will be effective if the communicator is considered a trusted and knowledgeable source, as discussed previously. What needs to be remembered when making recommendations about biosecurity control measures is that primary producers tend to invest first in practices that can be trialed before adoption and those that will lead to a relative advantage (Pannell et al. 2011; Sherman et al. 2019). There is often little incentive to invest in biosecurity preparedness preincursion if the investment is not considered immediately useful and/or the return on investment cannot be ascertained easily relative to other strategic investment decisions. This requirement might explain why many people hope for the best and build their actionable knowledge only when a crisis eventuates. Given that supply-chain intermediaries often play an important role in biosecurity (Hulme et al. 2018; Turkson and Okike 2016), engaging them presents a potential pathway to influencing decisions of primary producers about preventative actions (Mankad et al. 2019).

Maintaining science credibility. From the preceding discussion, it should be evident that one-way transfer of potentially disconnected information about the biological and physical aspects of a pathogen incursion may not be helpful to stakeholders who need to deal with the socio-economic complexities and uncertainties around shaping and implementing biosecurity policies. Moreover, the credibility of science and the professional integrity of scientists is at stake when a given problem is inappropriately framed as a science rather than a political question. For example, knowledge of the location and area of host plants, while important for understanding disease epidemiology, requires cooperation between industry, government, and the community to ensure the biosecurity authority has up-to-date intelligence at the time of an incursion. In each state and territory of Australia, for example, there is a regulatory requirement for property identification codes (PICs) (e.g., Anonymous 2020b) for those who trade or move livestock such as cattle, sheep, goats, and pigs; however, equivalent regulatory policy for plant industries is only just beginning to emerge. Even so, a group of farmers might expect the biosecurity authority to know where a pathogen will spread even though the distribution of host plants may be unknown. Scientists who fill this knowledge gap must be mindful of where and how new information might be used for political purposes.

Conclusions

Scientists and their host organizations must take a wide view of the system in which the biosecurity problem is situated. By applying a problem focus rather than a solution focus, scientists gain a deeper understanding of the on-ground tasks being undertaken during an incursion, and the pain points associated with getting a job done. When people learn about a problem from another’s perspective, there is a greater likelihood of achieving timely agreement on what will be done to solve the problem, even though individual goals may vary (De Haan and De Heer 2015).

Central to the postincursion response and its outcomes are the people involved and how they interact with each other at different scales, even around actions that are nonnegotiable due to regulatory protocols. Effective biosecurity leaders will manage stakeholder expectations and negotiate trade-offs among groups who may hold different values and goals. Activities that promote colearning with stakeholders can highlight the necessary trade-offs to them. Affected stakeholders who engage and participate ahead of a threat will recognize it as an investment to build enterprise and system resilience.

Others will have no incentive to engage preemptively and may view it as an opportunity cost.

Understanding the process for biosecurity risk assessment, response, and recovery helps scientists contextualize knowledge needs of stakeholders as well as inform appropriate knowledge flows. A key area of contention among biosecurity stakeholders are decisions around disease eradication. In all cases, the eradication plan must have the potential to be implemented readily and cost-effectively. Otherwise, containment and/or transitioning to long-term management must consider collection of appropriate epidemiological data and sense-making through application of relevant digital and bioinformatic technologies.

An appropriate and timely biosecurity response—the ultimate solution—is more likely when scientists work collaboratively with stakeholders so the solution draws upon different types of knowledge, not just “expert” knowledge (Evans et al. 2017). Most people know intuitively that science can only make a partial contribution to resolving complex problems (Jasanoff 2007). When knowledge is codelveloped with stakeholders, there is interdependency between knowledge and action (Miller and Wyborn 2018). Those who will eventually adopt a solution, such as a system for disease monitoring and assessment, will have shaped its development through their involvement.

Given the socio-political contexts described here, we argue that the nature and timing of knowledge flows—right people, right time, right place, right rules, right tools—is just as important as building the knowledge base and supplying science-based information. Effective knowledge flows require scientists to become part of a complex, adaptive system involving effective learning and knowledge development, exchange, and use. Through this approach, new information introduced into the system has a greater likelihood of being perceived by a target audience as being salient, legitimate, credible, and actionable.

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