Sampling to Support Claims of Area Freedom

Technical Report for the Department of Agriculture

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Executive Summary

This report outlines a general method for estimating the optimal level of surveillance effort for making claims of eradication and/or area freedom. We assert that agencies should seek to minimise the net expected costs of surveillance and the expected damages that would occur, should the pest still be present. This approach builds on the existing paradigm that is used for 'proving' freedom from a pest or disease, which specifies a probability that the pest is detected if present at a nominated prevalence, but provides no insight as to how the probability or prevalence should be set. By wrapping the existing approach in an economic framework, we can shed light on the implications of different choices from the point of view of making decisions.

Our method is suited to surveillance that targets hosts that are infested with a pest or disease in regions where it can be assumed the risk of infection is homogeneous. It is not suitable for surveillance targeting pests that are independent of their hosts (e.g., fruit fly) unless the sensitivity to detect a given population size is known, or where risk is expected to vary spatially. Moreover, because our focus was to develop a model that was easy to parametrise with information commonly available to practitioners, the model does not account for absolutely all of the potential considerations. Nevertheless, we claim that our model will assist agencies to more readily determine the level of surveillance that they need to undertake by making explicit many of the factors that are usually vague, implicit, or omitted in discussions about proof of freedom.

We illustrate the method's implementation using information contained in two historical proof of freedom proposals conducted in Queensland for cocoa pod borer (*Conopomorpha cramerella*) and citrus canker (*Xanthomonas axonopodis*), and contrast the differences in the required levels of effort.

The method has been programmed as an interactive web application (https://apps.cebra.unimelb.edu.au/pof/) to increase user accessibility and to facilitate discussion around sampling effort in terms of costs and benefits.

1 Introduction

International trade in commodities operates via a rules-based system within which plant products that are claimed to be free of pests and/or diseases (hereafter, pests, following FAO, 2007) can be traded without the need for additional phytosanitary measures. Consequently, a strong economic incentive exists for countries to gather the evidence that is required to claim that they are free from a broad suite of harmful pests. This evidence is typically obtained from a variety of sources including: general surveillance, peer-reviewed publications, databases and internationally recognised targeted surveillance programs that provide evidence for claims of area freedom — that is, that the surveyed area is very likely to be free of regulated pests.

Claims of area freedom generally arise within three different decision contexts:

1. The pest has never been detected in, or was long ago eradicated from, an area;
2. The pest has recently been detected, and is under official control; and
3. The pest is endemic in an area, but a sub-area wishes to claim freedom.

The question of how to optimally design surveillance in order to justify claims of area freedom in all three contexts is long standing. Commonly, rules of thumb are deployed, such as sampling 600 units to provide at least a 95% confidence of detecting a pest at a prevalence of 0.5% or above, with ISPM 31 (FAO, 2008) being invoked as justification. However, specifying the confidence of detection is unhelpful without also considering the cost of surveillance, the cost of failing to detect the pest, and whether the chosen prevalence appropriately reflects the tolerable threat level of the pest. That is, an optimal surveillance design must be informed by biology to know how large of a population presents a material risk, and economics to know the consequences of failing to detect the population. The framework outlined in the following chapter attempts to integrate these fundamental decision factors for determining the optimal surveillance effort in order to claim area freedom.

2 General Framework

It is practically impossible to 'prove' that a pest is absent from an area as large as Australia. To do so would require a surveillance method with perfect sensitivity – a feat rarely obtainable – coupled with a complete, simultaneous, census of all susceptible hosts (or areas) across the country. As a consequence, absence is invariably inferred based on a notional level of confidence – the probability we would have detected it, had it been present. This confidence is commonly informed by: a pre-defined level of pest prevalence known as the design prevalence; by how good we are at detecting a pest per unit surveillance effort (surveillance sensitivity); and, how hard we have looked (surveillance effort).

What remains unclear is how confident we need to be to make a claim of freedom. Commonly, the level of confidence required is either set based on traditionally used arbitrary thresholds (e.g., 0.95 or 0.99) or based on an importing country's appropriate level of protection (ALOP). In either case, the costs involved in achieving these confidence levels may be greater than the potential impacts of a pest establishment, or may be vastly inadequate, particularly if the immediate and future costs of prematurely declaring freedom are high. Here, we propose that when the risk of future damages is high, we should seek to be more confident that the pest is absent and, conversely, when the risk is lower our level of confidence need not be as high.

2.1 Minimising Net Expected Costs (NEC)

The premise of our framework is that the net expected costs of surveillance should be minimised. That is, the optimal surveillance effort is the one that minimises the sum of the costs of surveillance and the expected costs of incorrectly claiming absence. Within this framework, as surveillance effort increases so too does our confidence that the pest is absent. Higher confidence implies lower chances of incorrectly claiming absence, and thus, lower chances of incurring additional surveillance and market costs (e.g., additional time out of market and re-eradication costs). However, in order to achieve higher confidence, we must invest more into surveillance effort, which in turn, increases surveillance costs and the time required to implement it. Here, we seek the point at which the marginal cost of doing additional surveillance is equal to the expected costs of incorrectly claiming that the pest is absent. This point is the optimum effort.

2.2 Mathematical Approach

This approach can be presented as a mathematical function (eqn. 2.1). The function has two distinct parts. The first term captures the costs associated with the surveillance, and the rest captures the costs associated with incorrectly declaring absence. To identify the optimal surveillance effort (captured as the number of surveys), we calculate the net expected cost for each possible number of surveys (n) and plot the results to locate the minimum.

$$\text{NEC}(n) = \text{Cost}_{\text{Survey}}(n) + \text{Cost}_{\text{Market}}(n) + \Pr(\text{Detection failure}|n) * \text{Cost}_{\text{Wrong}}(n), \quad (2.1)$$

where $\text{Cost}_{\text{Survey}}$ is the cost of undertaking the surveys, $\text{Cost}_{\text{Market}}$ is the cost associated with time out of market, $\Pr(\text{Detection failure}|n)$ is the probability that the species is still present and undetected after n surveys, and $\text{Cost}_{\text{Wrong}}$ is the cost associated with incorrectly declaring a pest is absent. This last cost includes additional damages associated with persistence of the pest and the future loss of market access. It also includes additional spending for eradication and surveillance. Here we are assuming that the surveys will return nil finds, and do not consider the case in which a positive find is returned by the area freedom survey. The exact form of these terms will depend entirely upon the species being considered, and are considered in detail in the case studies outlined in this report (see Chapters 3 and 4).

2.3 Specific Model Components

The Net Expected Costs (NEC) equation (eqn: 2.1) outlines a generic, high-level function that incorporates a range of costs that decision-makers must contend with when making decisions as to how much surveillance should be done. This function is not definitive because some costs may be negligible, irrelevant or missing for particular pests. Moreover, our focus was to develop a model that was easy to parameterise with information commonly available to practitioners, so we have ignored several factors that in most cases are unlikely to significantly influence the results. For example, our model does not explicitly account for changes in the value of money over time, or the probability that any subsequent re-eradication attempts are also unsuccessful.

2.3.1 Are You Risk Averse or Risk Neutral?

As outlined above, the core tenet of our framework is that the optimal amount of effort (i.e., samples) is the one that minimises the net expected costs of surveillance. Thus, we are not seeking to prove (i.e., be absolutely sure) that a pest is not present in an area; rather we are estimating how confident we need to be that a pest is not present at some specified prevalence in order to minimise the costs of both the surveillance and those that would be incurred if we failed to detect the pest, should it be present. The rationale for this approach is that surveillance is a diminishing marginal return activity; that is, each additional survey or sample results in less and less benefit. Because surveys cost money, we argue that surveillance should cease once the costs of additional surveillance are greater than the expected benefits arising from that additional surveillance.

These two contrasting approaches could be characterised as risk averse and risk neutral (or risk minimisation and risk management), respectively. Historically, biosecurity agencies have been risk averse when it comes to claiming proof of freedom, however, it is important to recognise that risk aversion incurs an opportunity cost. In such a circumstance the resources allocated to surveillance can't also be allocated to another biosecurity activity so the benefits of that alternate opportunity (which may be higher than those of the additional surveillance) are not realised. Because biosecurity agencies make a large number of investment decisions, the net effect of being risk averse (or so-called 'gold plating') for individual decisions is to diminish the overall risk reduction. Thus, we argue that when determining the values of the parameters to be used in our model, agencies should use the 'most likely' (risk-neutral) estimates as their guide, but also model both the 'best case' and 'worst case' in order to get an understanding of how the optimal level of effort varies between different scenarios before making a final decision on the required level of effort.

2.3.2 What are the surveillance costs?

Our primary consideration is the cost, both in terms of time and money, of undertaking surveillance. This includes:

- Cost of surveillance infrastructure;
- Cost of inspection (labour cost);
- Cost of testing (laboratory cost); and
- Proportion of samples requiring laboratory testing

Depending on the context, it may also include the fixed costs of operating a trapping network or the daily cost of keeping an incident control centre open during post-outbreak surveillance. Surveillance costs may increase linearly or non-linearly with the number of surveys. We describe it as:

$$\text{Cost}_{\text{Survey}}(n) = (\text{Cost}_{\text{infra}}(1) + \text{Cost}_{\text{insp}}(1) + (\text{Cost}_{\text{lab}}(1) \times \text{Rate}_{\text{test}})) \times n, \quad (2.2)$$

where n is the number of surveys, $\text{Cost}_{\text{infra}}$ is the cost of surveillance infrastructure (e.g. a trap) and $\text{Cost}_{\text{insp}}$ is the cost per survey, such as visually inspecting a host for symptoms. If any material collected from an inspection is suspect, then Cost_{lab} is the cost of undertaking a diagnostic test to confirm the result, and $\text{Rate}_{\text{test}}$ is the expected percentage of suspect samples likely to require this diagnostic verification. For example, when conducting surveillance for a plant disease there could be a number of conditions that present similar visual symptoms, necessitating a laboratory test for definitive disease verification.

2.3.3 Designing surveillance

The surveillance design parameters describe the pest biology and how they interact with surveillance. When making statistical statements about absence given surveillance data, three fundamental parameters are required – 1) the **sensitivity** of a surveillance unit (e.g., survey unit) to detect the pest; 2) the pest **prevalence** one wishes to detect; and 3) the amount of **surveillance effort** undertaken. We next discuss each of these parameters.

2.3.3.1 Choose the surveillance sensitivity

Here, sensitivity describes the probability that a diagnostic test, trap or survey detects an object given it is present (Cannon, 2002; Barrett *et al.*, 2010); it can be considered a measure of surveillance reliability. The sensitivity of a surveillance unit must be known in order to make inferences about the absence of a pest. If sensitivity is perfect (i.e., the probability of detecting the pest is 1 when the pest is present), then there is absolute confidence that the object of interest will be detected when present. By contrast, if sensitivity is low, then there is little confidence that the object of interest will be detected, and thus, observed absences may result from failed detections.

Surveillance programs never have perfect sensitivity (Kery, 2002; Royle & Link, 2006; Hauser & McCarthy, 2009). Furthermore, estimating surveillance sensitivity can be difficult because it can vary substantially among species and is influenced by many factors including: species traits (Garrard *et al.*, 2012), the amount of surveillance effort (e.g., number of surveys, tests, traps undertaken, survey time; Garrard *et al.* 2008; Hauser & McCarthy 2009), the prevalence or local abundance of the species (McCarthy *et al.*, 2013), site conditions, weather conditions, time of day, and observer or surveillance attributes (Bailey *et al.*, 2004; Garrard *et al.*, 2012). As a consequence, decisions about the required surveillance effort needed to detect a pest, particularly plant pests, are routinely based on either assuming perfect detection (see, e.g., Hoffmann & Robinson, 2014) or meeting minimum standards that are not underpinned by a statistical framework (Whittle *et al.*, 2013), and thus, do not provide an empirical estimate of sensitivity (e.g., fruit fly surveillance; International Atomic Energy Agency 2003; Anon 2008).

Despite these difficulties, information about sensitivity can be obtained in most situations. In applications where presence and absence data are available and a population can be assumed to be closed (i.e., no immigration or emigration), models can be developed to estimate sensitivity by repeatedly sampling populations (e.g., Royle & Kery, 2007)[1]. Other approaches include conducting experiments that explicitly estimate sensitivity under a variety of conditions (Hauser *et al.*, 2012, 2016), using known detection rates from similar species or species with similar traits (Garrard *et al.*, 2012), conducting meta-analyses using data derived from published experiments, or when no other data are available, by the use of expert judgement (Garabed *et al.*, 2009; Barrett *et al.*, 2010; Jarrad *et al.*, 2011b,a).

2.3.3.2 Choose the maximum tolerable prevalence

The maximum tolerable prevalence that a pest may exhibit before unacceptable impacts occur is also of critical importance when determining the optimal amount of surveillance. Higher prevalences are generally easier to detect. Choosing the prevalence will likely be a trade-off between being high enough to detect, and low enough such that a detected outbreak can be controlled or eradicated. Martin (2017) proposed that the prevalence be set such that it is:

- high enough that it is detectable;
- low enough not to cause unacceptable impacts on human health, the environment or other values;

[1] This approach is unlikely to be suited to biosecurity questions as it implicitly assumes the pest is in equilibrium with its environment and absence data are rarely available for invasive species.

- low enough that action could be taken to eliminate or control the pest if it were detected; and
- is acceptable to trading partners (or others with an interest in the outcome)[2].

Due to difficulties in conceptualising what a maximum tolerable prevalence looks like, we ask users to define the total susceptible population of hosts in a region of interest (Biol_{pop}) and the maximum tolerable number of individual hosts that may be infected ($\text{Biol}_{\text{max infected}}$) — essentially, the smallest size of the infected population that *must* be detected. We then use these numbers to determine the maximum tolerable prevalence $\text{Biol}_{\text{prev}}$, using:

$$\text{Biol}_{\text{prev}} = \frac{\text{Biol}_{\text{max infected}}}{\text{Biol}_{\text{pop}}} \tag{2.3}$$

The web application has been designed for dealing with host dependent pests (e.g. diseases), where a tolerable infection prevalence is meaningful. However, the application could also be used for non-host dependent pests such as fruit fly, IF sensitivity is estimated in terms of detecting a particular population size. If this is the case, $\text{Biol}_{\text{prev}}$ should be equal to 1.

2.3.3.3 Surveillance effort can then be determined

Surveillance effort, (n), is simply the amount of effort conducted to detect a pest. Commonly, this is measured as the number of surveys conducted, the number of samples taken, or the number of traps used. In our model, n is determined by minimising the net expected costs. However, we do ask users to set the maximum possible number of independent surveillance samples in order to constrain model estimates to what can be done given available resources.

2.3.3.4 Estimate detection failure

The probability of failing to detect a pest given it is present at the maximum tolerable prevalence, $\text{Biol}_{\text{prev}}$, with a given surveillance sensitivity, $\text{Biol}_{\text{sens}}$, and surveillance effort, n, is determined by:

$$\Pr(\text{Detection failure}|n) = (1 - \text{Biol}_{\text{prev}} \times \text{Biol}_{\text{sens}})^n \tag{2.4}$$

2.3.4 Set the market impact

Market access impacts are those that arise due to either direct changes in commodity prices as a result of an incursion or the need to treat goods (incurring a cost) in order to continue selling into a particular market. This results in a marginal reduction in market value during an outbreak, determined by the rate at which goods are produced multiplied by the reduction in value for those goods. As market access impacts depend on how long access is restricted for, we estimate the total time for markets to resume to

[2] This would require conducting a meeting where all interested parties agreed on prevalence value

be the maximum of either a fixed period, or the time required to complete sampling. This formulation is given as

$$\text{Cost}_{\text{Market}}(n) = \max\left(\text{Time}_{\text{min}}, \frac{n}{\text{Rate}_{\text{samp}}}\right) \times (\text{Price}_{\text{loss}} \times \text{Rate}_{\text{commod}}), \tag{2.5}$$

where Time_{min} is the minimum time the region will be unable to export due to external factors, such as a trade agreement whereby a fixed period of time must pass before area freedom can be re-instigated. This time is compared to the time required to complete the sampling ($\frac{n}{\text{Rate}_{\text{samp}}}$), where $\text{Rate}_{\text{samp}}$ is the number of samples that can be taken per day, and the maximum of the two is taken to determine the costs associated with being unable to sell to external markets. This is determined by the reduction in price per unit that this restriction causes ($\text{Price}_{\text{loss}}$) and the rate at which this commodity is exported per day ($\text{Rate}_{\text{commod}}$).

2.3.5 Determine costs if freedom claim is wrong

The final term required is the costs associated with incorrectly declaring freedom following an eradication program. This is the probability that the pest population was actually above our maximum tolerable infestation, in which case we assume that the pest has managed to survive and will begin to spread again. This will potentially require a new eradication program, unless eradication is determined to be infeasible, and result in an extended period where market access will be lost while re-eradication occurs. The costs associated with this are given by:

$$\begin{aligned}\text{Cost}_{\text{wrong}}(n) = \text{Cost}_{\text{erad}} + \text{Time}_{\text{erad}} \times (\text{Cost}_{\text{unit price}} \times \text{Rate}_{\text{commod}}) + \\ \text{Cost}_{\text{Survey}}(n) + \text{Cost}_{\text{Market}}(n),\end{aligned} \tag{2.6}$$

where $\text{Cost}_{\text{erad}}$ is the additional cost required to re-implement an eradication program, and $\text{Time}_{\text{erad}}$ is the time required to complete the eradication campaign. We also add the costs of conducting another round of surveillance and the associated market access costs.

3 Case Study: Cocoa Pod Borer

Cocoa pod borer (*Conopomorpha cramerella*) is a species of moth and a major pest of cocoa in South East Asia and the Pacific. It lays eggs on the cocoa fruit. Feeding by larvae causes discolouration and damaged pods contain fused and poor quality seeds. The pest was detected in April 2011 in an organic commercial cocoa plantation near Port Douglas in far north Queensland. Following eradication procedures a number of surveillance activities were conducted to declare proof of freedom. These surveillance activities included pheromone trapping, visual surveillance of mature fruit and supervised cocoa pod processing. Information for this case study was taken from the 2013 area freedom proposal for cocoa pod borer (DAFF, 2013). To illustrate the framework, we use the supervised cocoa pod surveillance data collected post-eradication. The first step of processing involved splitting the cocoa pods to examine signs of infestation – specifically, beans with pods surrounded by discoloured mucilage that cannot be easily removed. This approach to surveillance was used because it was extremely cost effective, given the beans had already been collected and that large volumes could be readily be inspected at a single location.

3.1 What are the Surveillance Costs?

3.1.1 Cost of trapping infrastructure

The focus of this case study was declaring freedom following eradication efforts using visual inspection data of pods at an existing processing facility. As such trapping infrastructure costs were set to zero in this case study (because no additional costs were incurred).

3.1.2 Cost of visual inspection

For this incursion, the Queensland Department of Agriculture Forestry and Fisheries spent approximately 6 FTE days during the 2013/14 financial year observing the processing of 5051 pods collected from commercial properties in the region. Assuming 1 FTE day involved approximately 6 hours of visual inspections (factoring in breaks), this equates to 36 person hours. Assuming a wage of $60 per hour (including on-costs) we can estimate the cost of surveillance to be approximately $0.43 per sample.

3.1.3 Cost of diagnostic testing

External diagnostic tests were also required in order to confirm the damage was as a result of cocoa pod borer (*Conopomorpha cramerella*) infestation. This is because while the symptoms exhibited within cocoa pods are distinctive and the moth was able to be reared from damaged pods, positive identification of the pest is challenging. The adults are highly similar to the native moth *C. litchiella*, and a genital dissection was done to provide complete confidence the collected adults were invasive and not the similar native species. As Cocoa pod borer was verified prior to eradication efforts, all sampled pods post-eradication displaying symptoms were assumed to be caused by Cocoa pod borer, and as such no additional validation diagnostic was undertaken. This meant that there were no diagnostic costs during this surveillance period.

3.1.4 Set expected proportion of samples requiring diagnostic testing

As no diagnostic tests were required for this case study (see above), the proportion was set to zero.

3.2 Surveillance Design

3.2.1 Determine the maximum tolerable prevalence

3.2.1.1 What is the total population at risk?

In this case study, surveillance for proof of freedom was conducted on individual cocoa pods during processing as opposed to surveillance on individual host trees. As such, our unit of measurement is the number of cocoa pods in the region of interest. As the freedom proposal did not specify the total number of cocoa pods being grown or processed in the infected region, we assumed that exhaustive sampling (i.e., a census) was done, and thus, the total population of cocoa pods in the region was 5051.

3.2.1.2 What is the maximum tolerable infested population?

The pest was initially detected during pod processing, however it is unknown how many years the pest may have been present but undetected at the site. Moreover, the area freedom report did not document a tolerable prevalence or a tolerable number of infected pods. For illustrative purposes we assumed that the maximum tolerable number of infected cocoa pods was 50, which as a proportion of the total population gives us a maximum tolerable prevalence of 1%.

3.2.2 What is the sensitivity of surveillance?

The sensitivity of pod inspections during processing was also unknown, however, because the visual symptoms of infected cocoa pods were pronounced, we assumed that the probability of detecting an individual infected pod during processing was at lowest 0.5 and at best 0.9. To show how uncertainty in surveillance sensitivity affects the results, we implemented the developed model using both estimates of sensitivity.

3.2.3 Choose the maximum samples

We set the maximum possible number of samples as 5051 (i.e., the whole population is inspected).

3.3 Determine the Market Impact

The cocoa industry in Australia is quite small and boutique. Most processing appears to occur locally and kills the larvae, so there appears to be no market access implications for the pest. As such market access parameters (i.e., *Minimum time out of market*, *Price change due to pest*, *Market volume affected*) were all set to zero.

3.3.1 What is the maximum sampling rate?

While this parameter is a surveillance design parameter, it has important ramifications on the time needed to regain market access, and as such we have included it under market impacts.

Based on information presented in the 2013 area freedom proposal for cocoa pod borer (DAFF, 2013) it took approximately 6 FTE days to visually inspect the processing of 5051 pods collected from commercial properties in the region. Here, we assumed this inspection was done by one employee over the course of 6 days, resulting in daily sampling rate of approximately 842.

3.4 Determine the Eradication Cost

3.4.1 What is the time required to re-eradicate?

We assumed that the time to re-eradicate and re-declare freedom of cocoa pod borer would be approximately 210 days (7 months). However, this parameter will not affect the estimation of net expected cost as market impacts have been set to zero.

3.4.2 What is the cost of re-eradication?

The initial eradication program cost approximately $100,000. If we incorrectly declare freedom due to a failed detection, it is likely that the incursion will remain undetected until it reaches similar prevalences as the initial outbreak. As such, we assume the re-eradication program would be $100,000 – the same cost as the initial eradication program.

3.5 Results and Discussion

The optimum surveillance effort was determined to be 854 samples when assuming sensitivity of 0.9 and 1,422 when sensitivity was 0.5 (Figure 3.1). These samples translate into confidence of cocoa pod borer absence, at a 1% prevalence, of 0.9995 and 0.9991 and associated net expected costs of $415 and $698, respectively.

When comparing these results to the actual surveillance effort implemented in the Queensland cocoa pod borer proof of freedom proposal (i.e., 5051 samples DAFF, 2013), we found that the number of samples were between 4 or 6 times more then what was estimated to be optimal. Based on model assumptions (see table 3.1) for parameters used), over sampling resulted in additional net expected costs over and beyond optimal of between $1,474 and $1,757. While this suggests that [relatively minor] savings could have been made by reducing sampling, there were undoubtedly operational constraints arising from the sampling method used (i.e., observing pods during processing), which may have made taking a smaller sample impractical or result in similar costs (e.g., the observer may have had to observe all of the pods being processed in order to take a smaller random sample).

The model highlights that high confidence levels were still achievable with the optimal sampling effort. In fact, high confidence, which translates to low probabilities of failed detections, are necessary in order to minimise the likelihood of incurring significant costs associated with re-implementing an eradication program (here assumed to be a cost of $100,000). If, however, the cost of eradication was substantially lower, or if the cost of surveillance was much higher, the level of confidence obtained from optimal sampling would be lower. This is because the benefit gained from avoiding potential costs associated with failed detections (e.g. re-implementing an eradication program) diminishes as surveillance costs increase at a higher rate relative to the avoided costs.

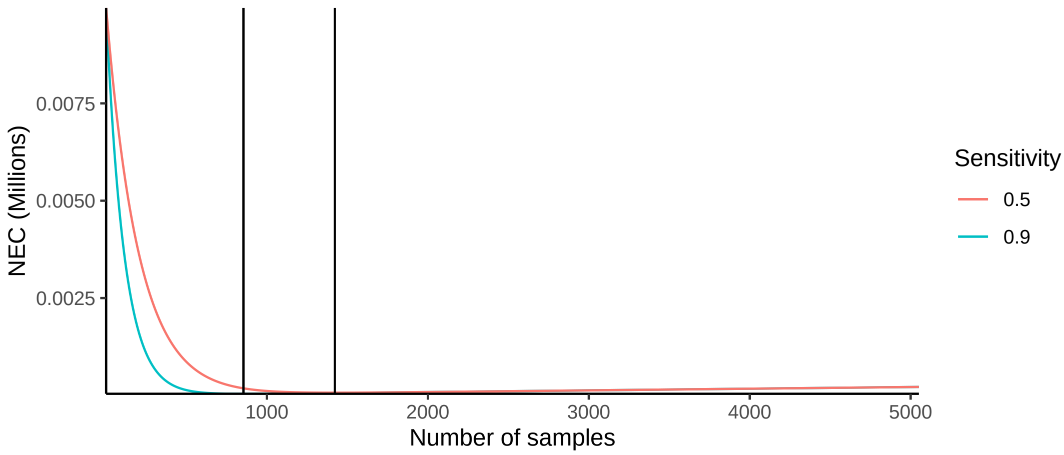

Figure 3.1: Optimum number of samples for claiming freedom from cocoa pod borer under two different sensitivity scenarios. Vertical lines signify optimal surveillance effort that minimises the net expected cost (i.e., 854 for sensitivity = 0.9 and 1,422 for when sensitivity = 0.5.)

3.5.1 Caveats

The results of this analysis are based on several strong assumptions including:

- **Sensitivity** – The area freedom proposal contained no estimate of the sensitivity of pod visual inspections. We therefore fitted the model with sensitivity set to 0.5 and 0.9. This encompassed the likely range of plausible sensitivity values, and is possibly at the higher end of this range due to the distinct symptoms of pod infection. However, without experimental verification, it is possible that sensitivity could be lower than 0.5, or some value between 0.5 and 0.9 that wasn't fit to the model.

- **Maximum tolerable prevalence** – The area freedom report did not provide definitive numbers on the total number of pods present in the region of interest. It also did not document what the maximum tolerable number of infected pods were or what the maximum tolerable prevalence (i.e., design prevalence). We therefore

Table 3.1: Parameters used for cocoa pod borer

Parameter	Value	Units
$Cost_{insp}$	0.43	$/Pod
$Cost_{lab}$	0	$/Pod
$Rate_{lab}$	0	Proportion
$Biol_{max\ infected}$	50	Pods
$Biol_{pop}$	5051	Pods
$Biol_{prev}$	0.01	Proportion
$Biol_{sens}$	0.5, 0.9	Proportion
$Time_{min}$	0	days
$Price_{loss}$	0	$/Tonne
$Rate_{commod}$	0	Tonne/day
$Rate_{test}$	842	Pods/day
$Cost_{erad}$	1e+05	$
$Time_{erad}$	210	days

assumed that the total population of pods in region was 5051 (i.e., all pods were inspected). We also assumed that the tolerable number of infected pods was 50, resulting in a maximum tolerable prevalence of 0.01.

- **Surveillance costs** – The primary surveillance cost was the number of man hours required to do the visual inspections. As this cost was not included within the area freedom report, we assumed an average hourly wage of $60.

- **Market impacts** – Because the Australian cocoa industry is small and boutique, and that most processing occurs locally and kills the larvae, we assumed there was no market impacts associated with this species.

4 Case Study: Citrus Canker

Citrus canker is a bacterial disease that affects citrus cultivars and causes cankerous welts on leaves, branches and fruit. It has been discovered in Australia and eradicated numerous times, most recently in Queensland in 2004 (DPIF, 2004, 2005, 2009) and Darwin in the Northern Territory in 2018 which is still ongoing. Citrus is a large export industry, but the majority of citrus is sold to countries that already have citrus canker present. Here we estimate the optimal surveillance effort required to claim area freedom for Queensland for 2015-2016. We parametrise this model using information presented in the Queensland proof of freedom proposals (DPIF, 2004, 2005, 2009) coupled with 2015-2016 market data reported in an ABARES report (Hafi *et al.*, 2018) as well as from the Australian Bureau of Statistics.

4.1 What are the Surveillance Costs?

4.1.1 Cost of surveillance infrastructure

Trapping infrastructure was not used for this disease, as such, costs were set to zero.

4.1.2 Cost of visual inspection

The primary method of surveillance was done by visually inspecting host trees. Unfortunately, the freedom proposals for citrus canker (DPIF, 2004, 2005, 2009) did not include details of surveillance costs. As such, we assumed that it would take an individual surveyor approximately 10 minutes to survey a tree (factoring in travel time). Assuming an average rate of $60 per hour (including on-costs), the cost per tree inspection would be $10.

4.1.3 Cost of diagnostic testing

Again, details on the number of verification diagnostic tests conducted was not presented within the freedom proposal. As such we assumed that laboratory testing for verification was a cost of $100 per sample.

4.1.4 Set expected proportion of samples requiring diagnostic testing

We assumed that 1% of trees inspected would require diagnostic testing in order verify the status of citrus canker like symptoms.

4.2 Surveillance Design

The 2004 and 2005 citrus canker proof of freedom proposals for Queensland used a block-based sampling regime, whereby a block contained a minimum of 500 commercial orchard trees but ideally 2000 trees. The number of blocks sampled was determined statistically such that there was a 95% chance of detecting a block-level infection prevalence of 1% with a sensitivity of detecting an infected block being 0.95. In the freedom proposal this equated to 175 blocks being sampled. Within each block, the number of trees sampled was set to 600 in order to achieve a 95% confidence of detecting a tree-level infection prevalence of 1% with a 0.5 surveillance sensitivity.

The framework we outlined above does not explicitly deal with this type of stratified/blocked sampling. Rather, it assumes a homogeneous population where the risk of infection is uniform and that random samples from a population may be taken. As such, for illustrative purposes, we will assume the population for Queensland is a single homogeneous population that is equally exposed to the pathogen.

4.2.1 Determine the maximum tolerable prevalence

4.2.1.1 What is the total population at risk?

Based on 2015-2016 Australian Bureau of statistics data (7121.0 - Agricultural Commodities, Australia, 2015-16), there are approximately 1,763,970 commercial citrus trees in Queensland. We therefore treated this number as our total number of at risk population.

4.2.1.2 What is the maximum tolerable infected population?

The maximum tolerable infected population was not reported within the proposal. However, a 1% infection prevalence was assumed at both the block and within block-levels. Assuming this equates to a region tolerable infection prevalence of 0.01% (i.e., 0.01×0.01), the maximum tolerable infected population for Queensland is expected to be 176 (i.e., $1,763,970 \times 0.0001$) individual trees.

4.2.2 What is the sensitivity of surveillance?

Experimental estimates of surveillance sensitivity conducted during the Emerald eradication program indicated that the sensitivity of the visual surveillance ranged from 0.42 to 0.76 depending on the size of the tree (DPIF, 2009). Based on these data, the area freedom proposal used a sensitivity of 0.5 when estimating confidence of detection. For the purposes of comparison, we estimated the optimal surveillance effort using sensitivity estimates of 0.5 as well as the upper limit of 0.76.

4.2.3 Choose the maximum samples

We assumed that the maximum number of commercial trees that could be inspected was 235,980. This corresponds to the number of trees sampled to declare proof of freedom for Queensland regions outside of Emerald and the Gayndah and Mundubbera management zone. It also suggests that the budget for visual inspections would be $2.36 million assuming surveillance costs of $10 per tree.

4.3 Determine the Market Impact

We use mandarins as our measure of market impact because Australian grown mandarins have the greatest exposure to citrus canker sensitive markets and also account for approximately 70% of Queensland citrus production (7121.0 - Agricultural Commodities, Australia, 2015-16). According to Hafi *et al.* (2018) in 2015-16, 39.1% of Queensland mandarins (28,994 tonnes) were exported to overseas markets at a gross value of $48.34 million, of which 8.3% (2,406 tonnes) went to citrus canker sensitive markets at a market value of approximately $4 million.

4.3.1 What is the maximum sampling rate?

The maximum number of trees inspected per day was not documented within the area freedom proposal. Here, we assume it takes an individual on average 10 minutes to visually inspect a tree (accounting travel time & differences in residential vs production sampling rates). Assuming a team of 10 people, each surveying for 6 hours a day, we estimate the daily number of trees inspected to be 360.

4.3.2 What is the minimum time out of market?

Citrus Canker does not contain a minimum time out of market restriction unlike other pests (e.g. fruit fly) and diseases (e.g. Foot and Mouth Disease). As such this parameter was set to zero.

4.3.3 What is the expected price change?

According to Hafi *et al.* (2018) the market value of mandarins exported to citrus canker sensitive markets would decrease by approximately 1.42% under the assumption that export market bans are brought in and mandarins are sold on the domestic market and non-sensitive overseas markets. Given 2,406 tonnes were exported at a gross value of $4 million in 2015-2016, the estimated per tonnage market value pre-incursion is estimated to be $1,663 per tonne. However, after the incursion this price would decrease to $1,639. The difference between these two numbers is our *price change*, which equates to a value decrease of $24 per tonne of mandarins that would otherwise be exported to citrus canker sensitive markets.

4.3.4 What is the market volume affected?

In 2015-2016 Queensland exported approximately 2,406 tonnes of mandarins to citrus canker sensitive markets. As we did not have information on the daily rate of exports to sensitive markets, we assumed this tonnage was exported at constant volumes across the year. That is we took the export volume to sensitive markets of 2406 and divided it by the number of days in the year (365) to derive the market volume impacted per day as approximately 7 tonnes.

4.4 Determine the Eradication Cost

4.4.1 What is the time required to re-eradicate?

We assumed that the time to re-eradicate Citrus canker will be 18 months (approximately 540 days). This was a similar time to initially declare eradication due to the need to ensure the depletion and eventual destruction of any residual bacterial inoculum that may have been present epiphytically, in detached host plant tissue, or within the soil (DPIF, 2009).

4.4.2 What is the cost of re-eradication?

The Queensland eradication campaign was completed in early 2009 and area freedom status for citrus canker was obtained for the Emerald growing district. The total cost of the eradication campaign was estimated at $17.6 million and required in excess of 200 000 staff hours to complete (Gambley *et al.*, 2009). Here, we assume that if citrus canker was rediscovered in 2015-16 the cost of re-eradication would be approximately $21 million (i.e., the initial 2015 eradication cost inflated to 2019 dollars).

4.5 Results and Discussion

The optimum surveillance effort was estimated to be 65,520 samples when assuming a sensitivity of 0.76 and 91,440 when sensitivity was 0.5 (Figure 4.1). These samples translate into confidence of citrus canker absence, at a 0.01% prevalence, of 0.993 and 0.9896, and associated net expected costs of $903,176 and $1,279,712, respectively.

When comparing these results to the actual surveillance effort implemented in the Queensland citrus canker proof of freedom proposal for regions outside of Emerald and the Gayndah and Mundubbera management zone (235,980 commercial trees sampled DPIF, 2004), we found that the number of samples were between 3 or 4 times more then what was estimated to be optimal. Based on our model assumptions (see table 4.1 for parameters used) this potential over sampling resulted in additional net expected costs over and beyond optimal of between $1,426,460 and $1,802,813. However, it is important to stress that many of our input values are best regarded as placeholders (that is, they're there to illustrate the method, rather than to be definitive), thus, it is important to not read too much into the results.

The model highlights that high confidence levels are still achievable with the optimal sampling effort. In fact, high confidence, which translates to low probabilities of failed detections, are necessary in order to minimise the likelihood of incurring significant costs associated with re-implementing an eradication program (here assumed to be a cost of $21 million). If, however, the cost of eradication was substantially lower, or if the cost of surveillance was much higher, the level of confidence obtained from optimal sampling would be lower. This is because the benefit gained from avoiding potential costs associated with failed detections (e.g. re-implementing an eradication program) diminishes as surveillance costs increase at a higher rate relative to the avoided costs.

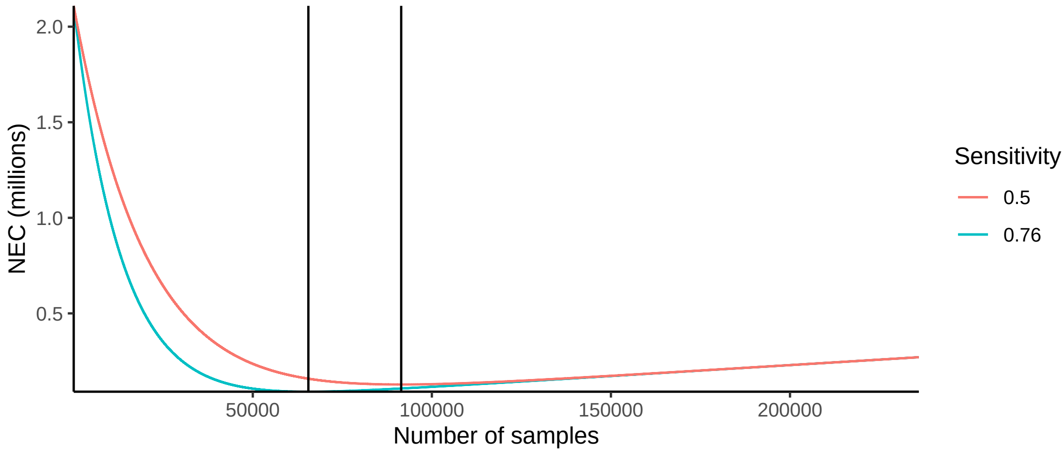

Figure 4.1: Optimum number of samples for claiming freedom from citrus canker under two different sensitivity scenarios. Vertical lines signify optimal surveillance effort that minimises the net expected cost (i.e., 65,520 for sensitivity = 0.76 and 91,440 for when sensitivity = 0.5.)

Table 4.1: Parameters used for citrus canker

Parameter	Value	Units
$Cost_{insp}$	10	$/Tree
$Cost_{lab}$	100	$/Tree
$Rate_{lab}$	0.01	Proportion
$Biol_{max\ infected}$	176	Trees
$Biol_{pop}$	1763970	Trees
$Biol_{prev}$	1e-04	Proportion
$Biol_{sens}$	0.5, 0.76	Proportion
$Time_{min}$	0	days
$Price_{loss}$	24	$/Tonne
$Rate_{commod}$	7	Tonne/day
$Rate_{test}$	360	Trees/day
$Cost_{erad}$	2.1e+07	$
$Time_{erad}$	540	days

4.5.1 Caveats

The results of this analysis are based on several strong assumptions including:

- **Surveillance costs** – The the average cost of visual inspection was $10 per tree. We also assumed that 1% of trees sampled would contain citrus canker-like symptoms that required laboratory diagnostics at a cost of $100 per sample.

- **Homogeneous population** – This analysis assumes that visual inspections are taken randomly across the entire state of Queensland. That is the host population in Queensland is treated as a single homogeneous population whereby all individual trees contain the same likelihood of being infected with citrus canker.

- **Maximum tolerable prevalence** – We used 2015-2016 ABS statistics to determine the number of citrus production trees present in Queensland. This number does not include non-production citrus varieties or native hosts, and therefore may be a substantial underestimation of the true population at risk of infection. Furthermore, the design prevalence used in the proof of freedom proposals was defined as 0.01 at both the block-level and the within-block level. As our model does not account for this hierarchical sampling, we assumed that this sampling method would result in a maximum tolerable prevalence of 0.0001. This is turn translates to a maximum tolerable infected population across QLD of 176 trees. In reality this may actually be higher or lower than what managers hoped to achieve given the hierarchical sampling.

- **Rate of sampling** – We assumed that on average it will take 10 minute to sample a tree (factoring in travel time, differences between residential vs production areas). We also assumed a team of 10 people would be employed to do the visual inspections whereby each would spend 6 hours a day inspecting trees, resulting 360 trees sampled per day. This rate of sampling may be too high or too low relative to what occurs in practice.

- **Market impact: damages over time** – We assumed there was no additional time out of market beyond the time required to declare eradication.

- **Price changes** – Price change costs are based on QLD mandarin exports to citrus canker sensitive markets using data provided in Hafi *et al.* (2018). These price changes do not account for changes in price for other citrus varies, and thus may underestimate the true market impact of a citrus canker incursion.

- **Eradication costs** – We assumed that if an incursion were to occur in 2015-2016, the cost of re-eradication would be similar to the original incursion plus inflation ($21 million).

- **Time to re-eradication** – We assumed that it would take 18 months following an detection before Queensland could be re-declared as citrus canker free. However, if a subsequent detection was small and isolated from other host plants, this length of time may be a considerable over-estimate.

5 Concluding Remarks

Throughout this report we have argued that the optimal level of surveillance effort (i.e., samples) for claiming area freedom is the one that minimises net expected costs. That is, the level of effort is most appropriately determined by weighing up costs and benefits. For practitioners used to the apparent simplicity of the traditional ’95:5’ or ’99:1’ confidence:prevalence methods (that don’t obviously include these considerations) this might all seem a bit academic. However, the choice of whether to be 95 or 99% confident of having detected a pest at a particular design prevalence is, ultimately, about costs and benefits. Thus, the strength of our framework is that it makes clear the considerations that go into determining how confident one needs to be given the circumstances and uses those to calculate the required level of effort rather than relying on arbitrary confidence values.

By making these considerations explicit our framework (and the accompanying web app) is specifically designed to help facilitate conversations around how much effort is ultimately required before claiming area freedom (moreso than determining the exactly optimal level of effort). In particular, where there is uncertainty about the true value of a particular input (e.g., how sensitive our surveillance is), our framework can be used (as it is in the case studies) to easily compare, discuss and trade-off differences in those values in order to understand how they influence the required level of effort. Similarly, where there is uncertainty about multiple parameters, users may choose to construct separate ’best case’, ’worst case’ and ’most likely’ scenarios for comparison (noting our earlier comments about the implications of allocating resources based on worst case scenarios). When used this way our framework can help to progress discussions in a way that is simply not possible within existing frameworks.

5.0.1 Future Directions

1. Early conversations with stakeholders identified an important distinction between two types of scenarios, namely: (i) wishing to establish pest freedom in an area where the pest has previously been detected and eradication has been attempted, and (ii) wishing to establish pest freedom in an area where the pest has not been detected but is implicated for other reasons, for example that the pest has been detected in a neighbouring area. The current paradigm does not explicitly shed light on this distinction, and extending it to do so is beyond the scope of this report. We are confident that the problem is tractable and would involve a branch of mathematics referred to as Bayesian modeling.

2. Presently, we have a fixed cost of re-eradication in the case that a viable population remains undetected. An explicit linkage between invasive population size and the cost and probability of success of eradication would remove the need to identify the MTP, the maximum tolerable prevalence, because the consequences of undetected prevalence would then be included in the costs in a dynamic way,

meaning in a way that is sensitive to the consequences of changing invasive population size as a result of sustained failure to detect.

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