

## Report Cover Page

<b>ACERA Project</b>		
1004		
<b>Title</b>		
Post-border surveillance techniques: review, synthesis and deployment		
<b>Author(s) / Address(es)</b>		
Dr Susie Hester, School of Business, Economics and Public Policy, University of New England Dr Cindy Hauser, School of Botany, University of Melbourne Dr John Kean, AgResearch Limited, Christchurch, New Zealand Dr Terry Walshe, School of Botany, University of Melbourne Dr Andrew Robinson, Department of Mathematics and Statistics, University of Melbourne		
<b>Material Type and Status (Internal draft, Final Technical or Project report, Manuscript, Manual, Software)</b>		
Milestone Report 1		
<b>Summary</b>		
<p>Post-border surveillance is undertaken for a variety of reasons: to give evidence that a pest or disease is absent from a country, region or defined area, thus enabling access to particular export markets; to detect new pests and diseases early enough to allow for cost-effective management; to establish the boundaries of a known pest or disease incursion; and to monitor the progress of existing containment or eradication programmes.</p> <p>The body of literature in these four areas is largely aimed at improving post-border surveillance systems, although much of it is inaccessible to the biosecurity decision maker who is responsible for allocating resources for surveillance. Here we provide a classification system for discussing and comparing methods and tools that can assist with post-border surveillance, with a view to creating an accessible summary of available techniques. We also include a discussion of relevant statistical and economic concepts, methods for estimating detectability, and tools for decision making in the context of post-border surveillance.</p> <p>The purpose of this report is to create an accessible summary of available tools to assist biosecurity managers with planning, implementation and evaluation of post-border surveillance activities. The tools range in character from rules-of-thumb and simple formulae, to simulation models with user-friendly interfaces</p>		
<b>ACERA Use only</b>	Received By:	Date:
	ACERA / AMSI SAC Approval:	Date:
	DAFF Endorsement: ( ) Yes ( ) No	Date:

# **Post-border surveillance techniques: review, synthesis and deployment**

## **ACERA Project No. 1004**

Susan Hester, University of New England  
Cindy Hauser, University of Melbourne  
Andrew Robinson, University of Melbourne

Milestone Report

3 September 2010

## Acknowledgements

This report is a product of the Australian Centre of Excellence for Risk Analysis (ACERA). In preparing this report, the authors acknowledge the financial and other support provided by the Department of Agriculture, Fisheries and Forestry (DAFF), the University of Melbourne, Australian Mathematical Sciences Institute (AMSI) and Australian Research Centre for Urban Ecology (ARCUE). This work was partially funded by New Zealand's Foundation for Research, Science and Technology through contract C02X0501, the Better Border Biosecurity (B3) programme.

The authors are grateful to Mark Burgman for advice and support throughout the construction of this report and to the following people for discussions and comments on previous drafts of the report: Lois Ransom, Paul Pheloung, Mike Cole, Dane Panetta, Oscar Cacho, Bernie Dominiak, Greg Hood, Andrew Tomkins, Simon Blomberg, Randall Jones, Stephen Dibley, Joslin Moore, Aaron Dodd, Dean Paini, Nichole Hammond, Brendan Murphy, Tracy Rout, Mark Stanaway, Sama Low Choy, Peter Whittle, Tony Pople, Peter Baxter, Natalie Karavarsamis, Indriati Bisono, and staff of the NT Department of Resources who spoke at a project meeting on 26 and 27 October 2009.

## Table of contents

<b>Acknowledgements .....</b>	<b>2</b>
<b>Table of contents .....</b>	<b>3</b>
<b>List of Tables .....</b>	<b>5</b>
<b>List of Figures .....</b>	<b>6</b>
<b>Glossary .....</b>	<b>7</b>
<b>1. Executive Summary .....</b>	<b>11</b>
<b>2. Introduction .....</b>	<b>13</b>
<b>3. Key terminology and concepts.....</b>	<b>16</b>
3.1 <i>Estimating costs and consequences.....</i>	16
3.2 <i>Statistical terminology and concepts.....</i>	22
3.3 <i>Estimating detection probability .....</i>	31
<b>4. Prioritizing species and projects.....</b>	<b>36</b>
<b>5. Post-border surveillance techniques for single species .....</b>	<b>42</b>
5.1 <i>Market Access.....</i>	43
5.1.1 <i>The prospective approach .....</i>	46
5.1.2 <i>The retrospective approach .....</i>	53
5.2 <i>Early Detection .....</i>	55
5.3 <i>Delimitation.....</i>	65
5.4 <i>Monitoring.....</i>	72
<b>6. Decision making.....</b>	<b>79</b>
6.1 <i>Short-term decision making.....</i>	79
6.2 <i>Long-term decision making.....</i>	80
<b>7. Discussion .....</b>	<b>87</b>
7.1 <i>Recommendations for case studies .....</i>	88

**8. References ..... 91**

**9. Appendix ..... 99**

## List of Tables

Table 1 Tools that can be used for estimating population apparency or detectability.....	35
Table 2 Calculations of sample size with method accuracy adjustments (modified from McMaugh 2005) .....	48
Table 3 Examples of sample size calculations performed with a 95% confidence level (Source: McMaugh 2005) .....	52
Table 4 Surveillance tools for market access .....	55
Table 5 Surveillance tools for early detection .....	65
Table 6 Surveillance tools for delimitation .....	72
Table 7 Surveillance tools for monitoring.....	78
Table 8 Summary of deployable tools and techniques for long-term decision making ...	86
Table 9 A sample of potential case studies and illustrations from the Northern Territory	88
Table 10 ACERA projects of relevance to post-border surveillance.....	99

## List of Figures

Figure 1 Graphical presentation of optimal investment in management amongst species to minimize overall impacts .....	37
Figure 2 Hierarchy of prioritizing criteria for exotic plants pests, used by the USDA for CAPS. ....	40
Figure 3 Conceptual diagram of the phases of surveillance and infestation management .....	42
Figure 4 A mind map of tools and techniques for market access (.....	50
Figure 5 Comparison of risk estimates (D) for 2002 and 2007 data for the same localities. ....	57
Figure 6 A mind map of surveillance tools for early detection. ....	59
Figure 7 The effect of changing the tolerable population size ( $K$ ) on the number of required SSC units for <i>Rattus rattus</i> , for a power of 0.8.....	60
Figure 8 Application of Hauser and McCarthy's (2009) surveillance allocation model for ground searches of orange hawkweed on the Bogong High Plains .....	64
Figure 9 A mind map of surveillance tools for delimitation .....	69
Figure 10 A mind map of surveillance techniques and tools for monitoring and assessment.....	74
Figure 11 The probability that bitterweed is extant as a function of the number of consecutive absent surveys (shown up to $d = 20$ ), calculated with four different methods. ....	77
Figure 12 The optimal control expenditure, as a proportion of the initial value of the system.....	81
Figure 13 Example motif network configurations for Chades (2009).....	83
Figure 14 (a) Eradograph for a branched broomrape eradication project, and (b) recommended resource deployment as a function of eradograph trend .....	84
Figure 15 Simulated performance of invasive species management over 20 years by Baxter and Possingham .....	85

## Glossary

**Active surveillance:** the deliberate, coordinated searching for, diagnosis and reporting of pests and diseases by pest-management agencies.

**Actual Prevalence:** the true proportion of infested units in a population.

**Benefit-cost analysis (BCA):** a method used to assess the relative desirability of competing alternatives.

**Biosecurity:** the process of protecting the economy, environment, social amenity and public health from negative impacts associated with pests and diseases.

**Collateral data:** data that are not directly relevant to survey, such as data from other species, from another place or context.

**Containment:** the application of measures in and around an incursion of a pest or disease to prevent its spread.

**Compartment:** an animal subpopulation contained in one or more establishments under a common biosecurity management system, with a distinct health status with respect to a specific disease or specific diseases for which required surveillance, control and biosecurity measures have been applied for the purpose of international trade.

**Delimitation:** the process of determining the spatial extent of a pest or disease incursion.

**Design prevalence:** the pre-survey estimate of likely actual prevalence. It is the plant- or animal-level prevalence of a pest or disease to be used in calculating sample size. It is expected that the design prevalence (and actual prevalence) are near zero when claiming area freedom is the objective. A value for design prevalence will either be estimated (see McMaugh 2005 for further details) or a level chosen that is acceptable to all parties.

**Detectability:** the probability of a particular target individual being detected using a particular sampling technique.



**Discounting:** the process by which a future outcome (cost or benefit) is converted to a present-value monetary value.

**Discount rate:** the percentage rate used to reduce the value of a future income stream to its present value. Discount rates generally reflect two elements: time preferences (the desire to consume now rather than later), and a real return on capital (Moran *et al.* 1991). Discount rates are often the market rate of interest.

**Eradication:** complete removal of pest or disease (including, for weeds, propagules) from a particular area so that the target taxon can no longer be detected by recommended methods of survey for a defined period of time.

**Established (population):** a pest or disease, infestation or infection that is capable of perpetuation within an area after entry, for the foreseeable future.

**Estimated prevalence:** the prevalence that was found as the result of the survey. Ideally the result is a good estimate of the actual prevalence, although this may not be the case if survey methods have poor accuracy or sensitivity.

**Externalities:** in the surveillance context, these are the costs (or benefits) that are not borne (received) by the authority funding the surveillance activity.

**Fixed costs:** costs that must be paid at a given amount irrespective of the level of activity.

**Incursion:** an isolated population of a pest recently detected in an area, not known to be established, but expected to survive for the immediate future.

**Invasive species:** a species occurring beyond its accepted normal distribution and which threatens valued environmental, agricultural and other social resources by the damage it causes.

**Market access:** the conditions agreed by trading partners for the entry of specific goods into their markets.

**Monitoring:** surveillance undertaken to reassess a known infestation.

**Naturalised species:** a non-indigenous species originating elsewhere which has established and is reproducing itself without deliberate human intervention.

**Passive surveillance:** surveillance that relies on members of the public, industry groups, plant or animal health professionals and/or laboratories reporting suspected cases of plant or animal disease or the presence of a pest at their discretion. This may also include surveillance that uses existing information sources or networks of individuals or organizations.

**Pest Free Area (PFA):** an area in which a specific pest does not occur as demonstrated by scientific evidence and in which, where appropriate, this condition is being officially maintained.

**Risk analysis:** the process composed of hazard identification, risk assessment, risk management and risk communication (OIE 2009).

**Risk assessment:** an evidence-based process used to estimate the relative risk of species based on their biological characteristics, and their impact on agriculture, the environment, human health.

**Prevalence:** The total number of: individuals, or cases/outbreaks or new infections of a disease, or infestations of a pest, present in a population at risk (without distinction between old and new cases) in a particular geographical area, at one specified time or during a given period.

**Remote sensing:** the process of using non ground-based techniques such as aerial photography, multispectral airborne sensors; satellite imagery for surveillance.

**Satellite infestation:** a potentially eradicable population of a pest animal or weed arising as a result of spread from an established population.

**Sensitivity:** the proportion of truly positive units that are correctly identified as positive by a test.

**Specificity:** the proportion of truly negative units that are correctly identified as negative by a test.

**Surveillance:** the collection, collation, analysis, interpretation and timely dissemination of information on the presence, distribution or prevalence of pests or diseases and the plants or animals that they affect.

**Survey:** an investigation, in which information is systematically collected, usually carried out on a sample of a defined group or area, within a defined time period .

**Taxon** (plural: taxa): a taxonomic unit comprising closely related organisms, such as a particular genus, species, or subspecies.

**Variable costs:** costs that change with the level of an activity.

**Zone/region:** a clearly defined part of a territory containing an animal subpopulation with a distinct health status with respect to a specific disease for which required surveillance, control and biosecurity measures have been applied for the purpose of international trade.

## 1. Executive Summary

Post-border surveillance activities are undertaken for a variety of purposes: to achieve market access; to detect new pests and diseases sufficiently early to allow for cost-effective management; to establish the boundaries of a known pest or disease population; and to monitor the progress of existing containment or eradication programmes.

A significant body of literature has grown up around these four areas, principally aimed at improving post-border surveillance systems. Due to its complexity, however, much of this literature is inaccessible to the biosecurity manager who is faced with a range of surveillance problems and who is responsible for allocating a finite amount of resources to competing surveillance activities. Here we present a structure for discussing the methods and tools that can assist with decision making in the context of the varied aspects of post-border surveillance – which is broadly defined as planning, implementation and evaluation of activities – and undertaken for the purpose of market access, early detection, delimitation and monitoring. We summarize methods for estimating costs and consequences of post-border surveillance activities, which are essential for adopting a risk–return approach. Important principles of sampling design and estimation of detectability are also introduced and we review current tools for prioritizing the species that become that target of surveillance activities.

The purpose of this report is to provide an accessible summary of available tools to assist biosecurity managers with planning, implementation and evaluation of post-border surveillance activities. This report describes readily deployable tools that can be used to achieve a range of post-border surveillance objectives. The tools range in character from rules of thumb and simple formulae, to simulation models with user-friendly interfaces.



## 2. Introduction

The Ministry of Agriculture, Forestry and Biosecurity in New Zealand (MAFBNZ 2008) defines biosecurity surveillance as ‘the collection, collation, analysis, interpretation and timely dissemination of information on the presence, distribution or prevalence of pests or diseases and the plants or animals that they affect’. Although biosecurity surveillance occurs pre-border, at the border, and post-border, and many methods are relevant to pre-border surveillance, we focus this review on surveillance that occurs post-border.

The primary purposes of post-border surveillance are to provide evidence of absence of a pest or disease, and to determine the presence or change in prevalence or distribution of pests and diseases. By seeking to improve the way biosecurity surveillance is undertaken there is scope to improve the allocation of limited biosecurity resources, more effectively manage surveillance programs, and maintain important export markets. The outcome of biosecurity surveillance is a reduction in the risk that particular pests and diseases will become established or spread in a country or region, particularly those pests and diseases that have the potential to cause considerable harm to agricultural production, trade opportunities, human health, or valued ecosystems.

More specifically post-border surveillance is undertaken for a range of purposes, which we categorize as **market access; early detection; delimitation; and monitoring**. In this report we discuss many methods for planning, conducting and evaluating post-border surveillance in each of these categories, some of which are still conceptual or theoretical, while others are available for application. We distinguish between the conceptual and applicable methods by referring to the former as models or concepts and the latter, tools.

ACERA has invested in several projects that have developed models and tools for improving post-border surveillance and monitoring systems, with a particular emphasis on cost effectiveness and decision support (see Appendix A; Garrard *et al.* 2008; Hauser and McCarthy 2009; Cacho *et al.* 2010; Chades 2009, Rout *et al.* 2009a, b). These projects have created substantial new intellectual property in the form of search algorithms, cost-benefit equations, and decision protocols that can assist managers to allocate resources among competing surveillance priorities. This work by ACERA collaborators has complemented research that has been undertaken elsewhere (e.g. Hastings *et al.* 2006; Mehta *et al.* 2007).

Often the methods and tools developed for post-border surveillance are designed to apply to specific parts of the biosecurity continuum or specific decision making contexts. Some methods and tools account for uncertainty that arises from environmental variation or lack of knowledge, while others ignore uncertainty altogether. The Beale Review of Australia's biosecurity system (Beale *et al.* 2008) recommended that trade-offs between utility and risk be considered explicitly in resource allocation and decision making. Although the methods developed within ACERA and elsewhere are clearly relevant to the notion of risk-return in post-border biosecurity, each method applies to a different objective function with different assumptions and constraints. This report serves as a review of these advances in planning, conducting and evaluating post-border surveillance.

The objective of this multi-stage project is to identify and apply tools whose application will result in efficient allocation of resources among competing biosecurity risks to provide maximum public benefit. To achieve this objective, the project has been divided into six stages:

- Stage 1: Review and synthesize ACERA research
- Stage 2: Review and synthesize national and international research
- Stage 3: Develop scenarios, case studies and examples that illustrate the application of tools in circumstances relevant to their deployment in operational conditions in Australia, with end-user involvement.
- Stage 4: Develop and test simple software and spreadsheet applications that will facilitate the use of these tools in standard operating conditions in Federal and State agencies.
- Stage 5: Guide development of these tools by testing them iteratively in field conditions, and modifying the tools as required to suit a range of operational conditions, with end-user involvement.
- Stage 6: Develop guidelines and training materials and provide training opportunities for these tools (coordinating with the ACERA project for training in risk analysis tools)

In this document we present the results from Stages 1 and 2 – reviews and synthesis of relevant tools and techniques sourced from ACERA, national and international research.

This report is structured as follows. Methods and tools for **estimating costs and consequences**, which are essential for adopting a risk-return approach, are discussed in Section 3.1. We also introduce important principles of **sampling design** and **estimating detectability** for post-border biosecurity surveillance (Sections 3.2 and 3.3). The first phase of post-border surveillance is identifying which species to survey, and we review current tools for **prioritizing species** in Section 4. We review the academic literature and freely available tools from Australia and overseas that could be used to achieve the range of surveillance objectives discussed above, in Section 5. Since an important part of post-border surveillance is also to inform future planning and activities, we review the role of surveillance in the process of **decision-making** (Section 6). The report concludes with a discussion on progress towards the completion of Stage 3 (Section 7).



### 3. Key terminology and concepts

This chapter introduces and reviews important concepts and methods from economics, statistics and population ecology that apply in the post-border surveillance context. It is important to understand that resources for surveillance are finite so choices must be made between competing surveillance options. Techniques for evaluating benefits and costs over time are therefore critical in this regard and are discussed in Section 3.1. Statistical terms are used throughout this report because survey techniques and survey design are an integral part of many post-border surveillance activities. Key statistical concepts and well-known sampling designs are discussed in Section 3.2. Finally, understanding the likelihood of detecting a pest or disease, or 'detectability' is central to the quantitative surveillance tools reviewed in this report. We discuss experimental and empirical methods for estimating detectability in Section 3.3.

#### 3.1 Estimating costs and consequences

There are many instances in post-border surveillance when it becomes necessary to estimate and compare the benefits and costs that flow from alternative courses of action. Examples of scenarios include deciding whether to embark on an eradication campaign; deciding whether to invest in additional surveillance infrastructure; and deciding on the amount of resources that should be spent on early detection of an exotic pest or disease. In each of these examples, the benefits and costs of the alternatives should be estimated and compared before a particular alternative is chosen.

Resources are limited, so the choice between different post-border surveillance activities will involve a trade-off, or cost. Expenditure on one activity precludes expenditure on activities that were not chosen. Economists use the term *opportunity cost* to describe the cost of this choice: when a choice to do something is made in the face of resource scarcity, then an opportunity to do something else is given up. The opportunity cost of a particular project is calculated as the value of the highest valued alternative that has been foregone.

##### Benefit-cost analysis

Benefit-cost analysis (BCA) is a method that is used to assess the relative desirability of competing alternatives, where desirability is measured as economic worth to society as

a whole (see, for example, Sinden and Thampapillai 1995). The sequence of steps for undertaking a BCA is as follows (from Sinden and Thampapillai 1995):

1. Identify the problem and define alternatives to resolve it;
2. Identify the social benefits and costs of each alternative;
3. Value the benefits and costs of each alternative;
4. Tabulate the annual benefits and costs;
5. Calculate the net social benefit of each alternative;
6. Compare alternatives by their net social benefit;
7. Test for the sensitivity of the results to changes in assumptions and data; and
8. Make the final recommendation.

Because BCA normally involves comparing benefits and costs that arise at different points in time, they must be compared in ‘present-value’ terms through a process known as *discounting*.

### **Discounting**

Discounting is a key feature of BCA. It is the process by which a future outcome (cost or benefit) is converted to a present-value monetary value. Effectively discounting allows us to assess the opportunity cost that is connected with the delay in payment. The *present value* is the equivalent value today of a future benefit or cost. By discounting, we are acknowledging that a dollar received today is not worth the same as a dollar received tomorrow, because today’s dollar could be invested and earn interest. The formula for discounting when time is measured in discrete terms is:

$$PV = FV \frac{1}{(1+r)^t} \quad (1)$$

where  $PV$  is the present value of a future payment,  $FV$ , received in time period  $t$  at a discount rate  $r$  which is assumed to remain constant over time. Time is generally

measured in years, with  $t = 0$  representing the current year. The equivalent formula for discounting in continuous time is:

$$PV = FV \cdot e^{-\delta t} \quad (2)$$

where the discount rate is now represented as  $\delta$ . When time is taken as a continuous variable, the annual discount rate equivalent to a given value of  $r$  (in discrete time) can be estimated using the formula:

$$\delta = \ln(1 + r) \quad (3)$$

Discrete discounting assumes that all cash flows (receipts and expenditures) happen at the end of the year. Continuous discounting assumes that cash flows occur continuously throughout the year.

Discounting reduces the value of costs or benefits of a proposed policy, with the level of reduction depending on the discount rate and the number of years before society realises the costs or benefits (Ward 2006). Higher discount rates erode future benefits (and costs) more rapidly than lower rates. This becomes important when the benefits to society of a project are realised much later than when costs are incurred, which is often the case with projects that invest in environmental programs. Since the discount rate can influence the desirability of particular investments, using the wrong discount rate may result in economically inefficient decisions. Harrison (2010) describes the approaches for selecting a real (inflation-adjusted) discount rate as either being based on the opportunity cost of drawing funds from the private sector (using a market-based interest rate) or being derived from ethical views about inter-generational equity. Ward (2006) and Harrison (2010) review methods for choosing the discount rate in detail.

### **The benefit-cost ratio**

The benefit-cost ratio (BCR) is one of several methods that can be used to rank alternative courses of action. The simplest form of the BCR is the ratio of the benefits of a proposal relative to its costs, where both are expressed in present-values terms:

$$BCR = \frac{\sum_{t=1}^T B_t (1+r)^{-t}}{\sum_{t=1}^T C_t (1+r)^{-t}} \quad (4)$$

where  $B_t$  and  $C_t$  represent the benefits and costs, respectively, that accrue in year  $t$ ,  $r$  is the discount rate and  $T$  is time horizon of the evaluation.

An alternative form of the BCR is one that includes the ongoing operation and maintenance costs of the project in the calculation of benefits. In this case, the numerator in equation (4) would become net benefits (benefits minus operation and maintenance costs), and the denominator would be total capital costs. There are various other forms of the BCR (see Randall 1981) but the guiding principle is that the denominator of the ratio should be whatever is truly scarce in the context of the decision problem at hand (Randall 1981).

When the BCR exceeds 1.0, benefits exceed costs, when it equals 1.0 benefits equal costs, and when it is less than 1.0, costs exceed benefits. Note that projects that are being compared should be evaluated over the same period of time.

### **Net present value**

The net present value (NPV) is another method that can be used to rank alternative courses of action. NPV represents the sum of a flow of annual net benefits, where each is expressed in present-value terms. A positive NPV means a project or course of action is worthwhile pursuing, and a negative value represents the reverse situation. The formula for calculating the NPV is:

$$NPV = \sum_{t=1}^T \frac{B_t - C_t}{(1+r)^t} \quad (5)$$

Given a range of projects or investments to choose between, it would be economically rational to select the project or investment that resulted in the highest NPV, all else being equal.

## Valuing benefits and costs

Guidelines that should be followed when identifying true costs and benefits to be used in a BCA (Step b above, modified from Sinden and Thampapillai 1995) include the following:

- It is important to consider only those costs and benefits that accrue as a result of undertaking a particular project or decision; that is, the *extra* costs and benefits, rather than the total costs and total benefits of undertaking the alternative surveillance activity or project. For example, a biosecurity agency might have a range of fixed costs (e.g. rent on its building, electricity) that must be paid regardless of the activities it undertakes, but will also undertake a range of projects whose costs are in addition to the fixed costs.
- All positive and negative *externalities* should be identified, valued and included. In the surveillance context, externalities are the costs or benefits of an activity that are not borne by the authority responsible for funding that activity. Examples might be the extra costs faced by producers of selling animals when veterinary inspections become a requirement of trade from a pest-free zone, or where travellers must dispose of externally purchased items of fruit if they are to enter a fruit fly free area.

Some benefits and costs will be difficult to value because they are not directly traded in a market place and so do not get priced through the equilibrium of supply and demand. Examples of these 'unpriced' benefits and costs are those related to non-use and recreational values, such as the benefits to natural forests that arise from early-detection surveillance. Keeping invasive weeds out of natural areas maintains genetic diversity and amenity value of these places. In benefit-cost analysis, economists use two kinds of methods to estimate non-market values. The first is based on revealed preferences (e.g. travel costs; hedonic pricing; and supply and costs of protection - the defensive expenditure approach) and the second is based on stated preferences (willingness to pay - or accept e.g. choice modeling) (see Sinden and Thampapillai 1995 for a review).

The aim of stated preference techniques is to estimate the point of *indifference* in a choice between a non-market good and monetary cost (or compensation). An alternative to monetizing non-market values is to employ multi-attribute value theory (MAVT,

Keeney and Raiffa 1993), which retains benefits and costs in their natural units. MAVT may be merited where non-market values and emotionally demanding trade-offs need to be made (Luce *et al.* 1999). Chee (2004) argues that traditional approaches to economic valuation fail to capture social concerns around natural ecosystems and the services they provide. She advocates participatory approaches to decision-making that involve social learning, acknowledgment of uncertainty, negotiation and reconciliation of competing interests.

In MAVT, weights are elicited to describe indifference between two or more (market or non-market) attributes. Weights can be elicited using a variety of techniques (Hajkowicz *et al.* 2000), not all of which are credible. Indifference is a function of two things – the relative importance of attributes and the range of their consequences against the alternatives considered. A common mistake associated with some techniques is failure to make the range of alternatives salient to the respondent (e.g. direct weighting or pairwise comparisons used in the Analytic Hierarchy Process; see Steele *et al.* 2009, Keeney 2002). Techniques that explicitly require consideration of the range of consequences include ‘even swaps’ (Hammond *et al.* 1998) and swing weighting (Fischer 1995). The weights assigned to attributes should reflect the preferences of decision maker(s) acting on behalf of an organization or broader society.

A very common mistake in assigning weights is to ignore the range of consequences (Keeney 2002, Steele *et al.* 2009, ACERA 0607 and 0610). The incorporation of time preference (i.e. discounting) can be cumbersome, and there is no agreed theoretical basis for the aggregation of weights reflecting the preferences of multiple decision makers or stakeholders.

### **Alternatives to benefit-cost analysis**

Cost-effectiveness (CE) analysis and environmental impact (EI) analysis are alternatives to BCA. CE analysis is a method used to find the least-cost method of accomplishing some predetermined policy target, and is used when benefits cannot be measured.

When many alternative methods are available for achieving the particular target, marginal analysis is used to find the cheapest way of achieving the target. Programs are sought that will either increase the targeted output by the highest possible amount for a given expenditure, or to find the least expenditure of resources that will achieve the fixed

target (Ward 2006). The main disadvantage of CE analysis is that it cannot be used to analyse whether the benefits of the preset target are greater than the costs (Ward 2006).

EI analysis is used to assess the environmental impact of a policy when there is no information on either benefits or costs of a particular policy. With this method there is no attempt to convert consequences into a common value. Rather, decision makers and members of the public make decisions by assigning their own individual values to consequences, potentially resulting in a more democratic decision process (Ward 2006), although all non-environmental impacts are ignored during this process.

### 3.2 Statistical terminology and concepts

In this section we introduce and define relevant statistical terminology and concepts, and compare some simple and well-known sampling designs. For each design, we briefly describe the characteristics.

Formulae for estimating the total of the variable of interest and its standard error can be found in standard texts (for example, Cochran 1977, Krebs 1998). Schreuder *et al.* (1993) is an invaluable resource for more advanced designs.

#### Statistics concepts

*Population.* The population is the entity for which one wishes to estimate quantities of interest. The population comprises sampling units, and is in a sense co-defined with the sampling unit. It must be possible to represent the population by a frame. Examples of populations are the Wombat State Forest, and all the adults in Melbourne.

*Frame.* A frame is a list of units of the population, established to facilitate the selection of a random sample from the population. A frame for the Wombat State Forest might be a map, whereas a frame for all the adults in Melbourne might be a list of their names.

*Sampling unit.* The sampling unit is the unit selected from the population on which to conduct measurements. A sampling unit for the Wombat State Forest might be a fixed area within the forest of size (for example, 0.1 ha), whereas a sampling unit for all the adults in Melbourne would be an adult. The creation of discrete sampling units (plots) in a continuous plane such as a forest invariably involves some arbitrary decisions, for example, how large to make the plots, where to begin the grid, and what orientation to

adopt. However this arbitrariness has no significant influence on the outcome of sampling as long as it is carefully handled, for example, using random start locations and random orientation, and a plot size that is commensurate to the objectives of the sample design.

*Sample.* The sample is the collection of sampling units that are measured.

Settling upon a definition for the population and the sampling units can be tricky, especially in studies that involve assessment of biota. In thinking about sampling invasive species it is tempting, for example, to imagine that the population would be the population of invasives. But that would imply that the sampling unit would be an individual from the population and we would need a list of all individuals for the frame. In order to have such a frame we would have to know the population size. Therefore a more useful definition of the population would be the landscape that the invasives are suspected to inhabit; the sampling units are field plots or quadrats (i.e. small pieces of landscape that may be inspected for the invasives); the frame is the list of plots (or a map of the plots); and the sample is the collection of plots that is actually inspected. For many pests and diseases, the natural sampling unit is the host, that is, the plant or animal that is attacked by the invasive.

*Variable(s) of interest.* The variables of interest are the quantities that are measured on the sampling units. In the example in the preceding paragraph, the variables of interest might be the number of invasives on the field plot and some estimate of the damage that they have caused to the local biota.

*Statistic.* A statistic is an arithmetical function of data that reduces it to a summary. Example statistics are the total, the mean, and the standard deviation.

*Parameters.* The parameters are the population-level statistics of the variables of interest. Building on the earlier example, we might wish to know about the population total (parameter) of the invasive count (variable of interest) for a watershed (population). Other example parameters are the mean and the variance.

*Estimate (verb).* We estimate the population parameter using statistics calculated on the variable of interest as measured from the sample, and possibly other information.

*Estimate (noun).* The estimate is the outcome of estimation.



*Uncertainty.* All statistical knowledge is subject to sample-based uncertainty, which is uncertainty that is due to having measured only a portion of the population. We represent uncertainty using the *standard error*, which is computed using the information about the variation within the sample, among other things. Regan *et al* (2002) provide a detailed and useful discussion.

*Sampling distribution.* The sampling distribution is the distribution of values that could possibly be taken by a statistic given a set of data.

*Mean.* The mean is a measure of the location of the variable on the number line. The units of the mean are the same as the units of the data.

*Standard deviation.* The standard deviation is a measure of the spread of the variable on the number line. The units of the standard deviation are the same as the units of the data.

*Standard error.* The standard error is a measure of the spread of the sampling distribution of the estimate of the population parameter on the number line. The units of the standard error are the same as the units of the data.

## **Sampling**

The method used for selecting sites from which survey information is collected, the sampling plan, is an integral part of undertaking surveys to determine area freedom. Sampling should provide the best likelihood that the sample will be representative of the population, within the practical constraints imposed by different environments and production systems (OIE 2009). Here we present information about some basic designs and applications. Further information can be found in Cochran (1977), Schreuder *et al.* (1993) and FAO (2008b).

When it is not possible to sample all units or the whole population (a census), appropriate methods for unit selection are those that include at least some element of random sampling. In random sampling surveying, sites and hosts are chosen by an impartial method (i.e. through random number generation). This reduces the influence of human biases in the site selections. When selecting sites for plant pest surveys, random sampling, stratified random sampling, systematic sampling and flying insect trapping are all appropriate methods (McMaugh 2005). Having a random element in the survey

satisfies the recommendation from IPSM 6: that all survey plans should include some random sampling to detect unexpected events (FAO 1996:7). The approach selected will depend on the biological and dispersal characteristics of the pathogen and any financial or physical constraints.

*Simple random sample.* In simple random sampling, every combination of units has an equal probability of being selected. Sampling is commonly performed from a *frame*, which is a list of all the units in the population. Two versions of simple random sampling are possible: sampling with (SWR) and sampling without (SWOR) replacement.

Despite its apparent simplicity, when nothing else is known about a population, a simple random sample is the most efficient way to obtain information about a variable of interest, and should be considered a gold standard. Also, simple random samples are often much more difficult to perform correctly than might be apparent initially, because all possible combinations of units must have the same probability of being sampled. Such a prescription virtually demands that all members of a population are available for sampling, and that units be selected from this list completely randomly.

*Cluster sample.* A cluster sample is a sample in which collections of sampling units are selected as clusters, instead of as individuals. The clustering structure is pre-arranged, and is a characteristic of the system being sampled.

A cluster sample is not a simple random sample because the probability of pairs of sampling units both being included in the sample depend on whether or not the units are in the same cluster. Per unit measured, cluster sampling is less efficient than simple random sampling, meaning that on average the standard error will be higher for cluster sampling than for simple random sampling if the sample sizes are the same. When the total cost of the estimate is considered, however, cluster sampling may be more efficient in terms of the standard error of the estimate.

When a cluster sample is used, it is usually used for one of two reasons: first, if the spatial, temporal, or hierarchical structure of the population makes measuring clusters less expensive than measuring an equivalent number of unclustered units, and second, if a list of population units is not available but a list of clusters is available. An example of the first scenario is when the sampling units are scattered in space, and travel between

them is expensive. An example of the second scenario is when a list of people is not available, but a list of households is available, such as found in a telephone book.

Cluster sampling is at its most efficient when the clusters are as similar to one another as possible; i.e. when the within-cluster variation is high and the between-cluster variation is low. Even when no prior information is available about the population, however, cluster sampling may be preferred due to its greater cost-effectiveness if travel between units plays an important role. For a review of cluster sampling, see Turk and Borkowski (2005).

*Systematic random sample.* A systematic random sample requires the units to be located on a grid, usually of one or two dimensions. The sample involves selecting an initial sampling unit and then selecting every  $k$ th unit after the first. This approach is very efficient in terms of ensuring that the population is well covered by the sample. Systematic sampling is commonly used for spatial populations, for example in forest inventory. Systematic sampling can also be used when some auxiliary information is available; the frame is ordered by the auxiliary information and a systematic sample taken upon the ordered frame.

The only source of randomness in the sample is the selection of the first unit. Seen this way, a systematic random sample is a special kind of cluster sample, in which the population is divided into  $k$  intersticing clusters, only one of which is chosen. Therefore it may be argued that the true sample size of the systematic sample is one, and therefore that the standard error cannot be estimated. This view is a narrow one, and overly conservative; reasonable approximations are available (see, for example, Schreuder *et al.* 1993).

The approach to determination of the systematic sample depends on whether the grid that represents the population is one- or two-dimensional:

- For one dimension: Order the  $N$  units (the whole population) in some way, ideally according to an auxiliary variable that is correlated with the variable of interest. Take  $k$  as the nearest integer to  $N/n$ . Select the unit corresponding to a random integer within  $[1, N]$ , and every  $k^{\text{th}}$  unit after, circling as necessary.

- For two dimensions: Divide the total area  $A$  by  $n$ , giving the area represented by each point. The square root of the division is the desired inter-plot spacing, assuming a square grid. Use a random start point and a random rotation.

*Two-stage sample.* A two-stage sample may be performed when a population has structure for clustering, but the clusters themselves contain so many sampling units that inspecting entire clusters is impractical or seems undesirable. A two-stage sample involves taking a random sample of the clusters (which are referred to as primary sampling units or PSUs), and then for each PSU, taking a random sample of the sampling units that are within the cluster (referred to as secondary sampling units or SSUs).

An example of such a design would be the division of a landscape into identical polygons (PSUs) using a GIS, for example, selecting a sample of the polygons, and dividing each polygon in that sample into field plots (SSUs), and then selecting a sample of the plots independently within each polygon.

The common and readily available estimation apparatus for two-stage sampling assumes that the first and second stages will be simple random samples. Variants exist for other types of sampling, however, such as systematic and variable probability sampling (see, for example, Schreuder *et al.* 1993).

### **Using pre-existing auxiliary or prior information in sample selection**

We now describe designs that use auxiliary or prior information to sample the population more efficiently; i.e. to guide the sampling towards more informative collections of units. The prior information must be known for all the units in the population to be useful. These designs may be used in conjunction with those presented above, although estimation of the quantities of interest can become complicated. Examples of auxiliary information include cheaper and less accurate measures of the variable of interest, for example from remote sensing, or from an earlier census, or output from a habitat model that has been run for each unit in the population, or even an educated guess. Other examples of auxiliary information are variables that are likely related to the variable of interest, such as the outcomes of pathway models, habitat models, or vegetation classes, for example from remotely-sensed data. The key characteristics of useful

auxiliary information are that it be cheap, or already available, and that it be well-correlated with the variable of interest.

*Variable probability sampling.* Variable probability sampling, as its name suggests, allows the sampling units to be selected with variable probability. Ideally, the probability of selection should be proportional to the value of the variable of interest. The design then corrects for the different weighting when computing statistics (and their standard errors) by emphasizing each observation inversely according to its sampling probability. Positively-biased sampling is a form of variable probability sampling in which the sampling is biased towards that part of the frame that is considered more likely to contain the target species.

The advantage of such designs is that the variance calculation is based on the weighted data, rather than the raw data, and if the sampling probabilities correlate well with the variable of interest, then the weighted data are much less variable than the raw data. In the extreme case of perfect correlation, the uncertainty will be zero. Consequently, estimates of population parameters computed from good variable probability samples will be substantially less uncertain than estimates computed from constant probability sampling. This is an advantage conferred by skilful application of auxiliary information.

3P Sampling (Probability Proportional to Prediction) is an important variation of variable probability sampling that involves making an educated guess at the value for each sampling unit in the population, often in the process of deciding whether or not to measure it. This design originated in forest inventory, for which sometimes the process of reaching the sample points involves traversing much of the population. Variations exist that do not require the whole population to be predicted, such as point-3P sampling. This method may potentially result in substantial efficiency gains (see, for example, Schreuder *et al.* 1993).

*Stratified sampling.* Prior information may also be used to categorize the population into non-overlapping groups called strata. The strata are then treated as though they were distinct populations, and sampled independently. The sample designs within each stratum can vary freely, although they are commonly identical. The stratum estimates are then aggregated to provide an overall estimate using straightforward formulae.

Although stratified sampling seems superficially similar to cluster or two-stage sampling, there are some important differences. First, all the strata are sampled. Second, it is preferable for the units within each stratum to be as uniform as possible; that is, the best advantage is obtained from stratification when the within-stratum variation is small and the between-stratum variation is large. Informally, we can think of the stratification process as eliminating the between-stratum variation from the calculations of uncertainty.

Although stratification is most commonly performed using categorical auxiliary variables, it is of course possible to impose categories upon a continuous variable.

Experimentation has led to the rule of thumb that creating no more than six strata is about right for this approach, and fewer may be indicated if the population is small.

Having created strata, an added complication is that the sampler must nominate the number of sampling units to measure in each stratum. Three strategies are commonly advanced: (i) the same to each stratum (equal allocation), (ii) allocation of units proportionally to the stratum sizes (proportional allocation), and (iii) allocation of units proportionally to the stratum sizes multiplied by the estimated stratum variations (optimal allocation). The benefits should be carefully weighed against the operational complications. Proportional allocation is most commonly used. Cochran (1977) advised that if the projected uncertainty reduction of optimal allocation compared with proportional allocation was not less than 80% then proportional allocation should be preferred.

### **Collecting auxiliary or prior information and then using it in sample selection**

The benefits of using auxiliary information are often substantial. Sometimes it may be prohibitively expensive to collect auxiliary information for the entire population, but the expected benefits are sufficiently high that some kind of compromise seems attractive. Then collecting the auxiliary information can be integrated into the sample design.

*Two-phase sampling.* When a potentially helpful auxiliary variable can be identified but the cost of obtaining it over the entire population is prohibitive, a compromise may be struck. Two-phase sampling involves the following steps. First, take a large sample of the auxiliary variable, called the first-phase sample. This first-phase sample may then be treated as a population; that is, it may be stratified, or sampled with variable probability,

using the freshly collected auxiliary variable. The second-phase sample is taken from the units selected in the first phase, and an estimate of the total for the first phase is constructed. The resulting estimate of the total of the first-phase sample is then easily scaled up to represent the population.

Although two-phase sampling sounds complicated, the benefits can be substantial. In fact, owing to the diminishing returns effect of sample size, it is very likely that if the auxiliary variable is to be measured as part of the sample design, then two-phase sampling will be more efficient than collecting the auxiliary information for the entire population.

### **Using auxiliary or prior information in parameter estimation**

We now review analytical procedures that use prior or auxiliary information to construct more efficient estimates of the population parameters. These analytical approaches may be used in conjunction with some of the previously mentioned designs, and are very similar to others. Each assumes that auxiliary information is available, at least having been collected as part of the sampling process.

*Ratio estimation.* Ratio estimation has superficial similarities to the analysis of variable probability sample designs. Instead of computing the statistics of the variable of interest, the analyst computes the statistics of the ratio of the variable of interest and the auxiliary information for each unit in the sample (called mean of ratios), or the ratio of the statistics of the two variables (called ratio of means). Each of the two estimation procedures gives rise to estimates that have different statistical properties. Some authors claim that certain assumptions must hold for these estimates to be viable (see Gregoire 1998 for a refutation).

*Regression estimation.* Regression estimation may be thought of as a variant of ratio estimation that involves fitting a regression model between the variable of interest (as the response variable) and the auxiliary variable (as the predictor variable). The regression model is then applied to statistics that have been computed from the auxiliary variable, which is known for all the units in the population or, in the case of two-phase sampling, the units that have been selected for the first-phase sample. This application of the regression model allows the estimation of population parameters for the variable of interest.

### 3.3 Estimating detection probability

The quantitative surveillance tools reviewed in the following sections are influenced by detection probability, often abbreviated as the detectability. Confusingly, different authors have referred to the detectability of individuals (e.g. Cacho *et al.* 2007), of populations (e.g. Wintle *et al.* 2004) or of species (e.g. Mehta *et al.* 2007), often without explicitly stating in which sense they use the term. Here, we will use population *apparency* to be the probability that a local population of some non-zero size will be detected using a particular sampling or searching method, and *detectability* (sometimes termed ‘observability’, ‘trapability’ or ‘sample efficacy’) to be the probability of detecting a particular target individual. If all individuals have exactly the same chance of being found, then the apparency of the population  $a$  is related to the detectability of individuals  $d$  and the local population size  $N$  as

$$a = 1 - (1 - d)^N$$

(6)

If detectability varies between individuals – due, for example, to heterogeneity in size or visibility, or to spatial aggregation in location or search effort – then a more complex functional form will be required.

Both detectability and apparency (collectively referred to as *detection probabilities*) are determined by the characteristics of the target species, the survey method, and the sampling effort (e.g. mean search time) used, and may also be site- or time-dependent. The estimation of detection probabilities presents a significant challenge that must be met before almost all of the tools discussed in subsequent sections can be used. For example, several tools use variants of equation (6) to determine the optimal sample effort (number of traps, length of search, or number of repeat surveys) in order to achieve a high probability of detecting any extant population, based on the detectability of the target species (e.g. Regan *et al.* 2006, Bailey *et al.* 2007, Hauser and McCarthy 2009 and ACERA 0604, Rout *et al.* 2009a,b and ACERA 0604). A range of methods is available for estimating the detectability of various target taxa (e.g. plants, animals, disease symptoms) using either small, controlled experiments or empirical fits to larger data sets. In addition, some methods exist for the simultaneous estimation of detection probability and population size, but only for suitable sample designs (see below).



## Controlled experiments for measuring detection probability

Particular search methods may involve *bounded sampling*, in which a predefined area is searched with assumed uniform efficacy (e.g. vacuum samplers), or *distance sampling* (Buckland *et al.* 2001, Thomas *et al.* 2010), in which the search area is unbounded but detectability declines predictably with distance from a central sample point or transect line (e.g. visual surveys, attractive traps). In each case, custom-designed experiments may quantify detectability of the target taxon using calibration, mark–release–recapture or techniques involving non-independent samples. While these may allow the detectability to be estimated directly for a particular sampling scheme, in the case of distance sampling it is highly desirable to characterize the decline in detectability with distance because this allows the results to be extrapolated to alternative spatial arrangements of the sample tools (e.g. different transect lengths or trap spacings).

Calibration experiments involve simultaneously sampling the same population using two or more techniques. If the detectability using one technique is known, then the true population size can be estimated and the detectability using a second technique may be calculated (e.g. Fleischer *et al.* 1985, Byers *et al.* 1989), in some cases including the effects of covariates (e.g. Chen *et al.* 2009, Yackel-Adams *et al.* 2010).

Alternatively, mark–release–recapture methods allow the population size to be known (either as the population of marked individuals themselves, or through the standard methods for estimating the wild population size in such studies), enabling detectability to be estimated in various ways (Krebs and Boonstra 1984). With an appropriate design it may also be possible to quantify detectability in relation to covariates associated with target individuals, local environment, and searcher identity (e.g. Christy *et al.* 2010). Some studies have released a known population of simulacra, such as plastic insects or artificially induced disease symptoms, to estimate detectability in manual inspection surveys (e.g. Bulman *et al.* 1999, Murphy and Baird 2004).

Mark–release–recapture studies are particularly useful for characterizing the *effective sampling area* (Turchin and Odendaal 1996) or the *effective attraction radius* (Byers *et al.* 1989) of insect traps. Together with the spatial arrangement of traps, these allow apparency and detectability to be estimated. For particular trapping grids, detectability

may be estimated directly as the proportion of marked individuals recaptured after release. However, most mark–release–recapture studies to date have used point releases at the furthestmost point between traps, which means that they underestimate the detectability of randomly distributed individuals. An exception is the study by Elkinton and Cardé (1980), in which insects were released uniformly across the inter-trap area, resulting in an unbiased estimate of detectability. It is worth noting that sterile insect releases for population suppression may be used as mark–release–recapture experiments to quantify detection probability (e.g. Kean and Suckling 2005).

Calibration and mark–release–recapture techniques rely on known numbers of wild or marked individuals. If the true population size is not known in this way then another class of techniques, using non-independent samples, is available. For example, if a population is repeatedly sampled without replacement, then an accumulation curve may be derived (e.g. McCallum 2005) and detectability estimated from the slope and shape of the curve. For visual sampling, detectability can be estimated using double-observer methods, in which two observers simultaneously sample the same population (Nichols *et al.* 2000). Similarly, there may be potential for the effective sampling area of attractive traps to be inferred from their degree of interference at different spacings. Although this effect is well known (e.g. Wall and Perry 1978, van der Kraan and Deventer 1982), the methods necessary to estimate detectability from field results are currently lacking.

### **Empirical approaches to estimating detection probability**

A range of statistical techniques has been developed for simultaneously estimating apparency and/or detectability together with either local population size or probability of occupancy (e.g. MacKenzie *et al.* 2002, Tyre *et al.* 2003, Peterson and Bailey 2004). A comparison of these methods found that those based on empirically fitting zero-inflated distributions gave the best estimates for population apparency (Wintle *et al.* 2004), and there have been further advances in these models (e.g. Wenger and Freeman 2008, Joseph *et al.* 2009a). In tandem with the evolution of these methods, sampling theory has been developed to determine the optimal strategy for data collection to parameterize models. This may involve the choice of specific sampling methods (e.g. Rew *et al.* 2006, Cacho *et al.* 2007) or optimizing the trade-off between temporal and spatial replication (e.g. Mackenzie and Royle 2005, Bailey *et al.* 2007). For relatively immobile species, the

time spent searching at each site may be optimized, rather than the number of repeat visits (Garrard *et al.* 2008).

These empirical approaches have been derived primarily for use in conservation management, and typically require a relatively large data set (e.g. >3 surveys at each of >30 sites), which constrains their use in biosecurity surveillance, though there may be potential to incorporate relevant data from other times, places or species (Mackenzie *et al.* 2005). In addition, these techniques are inappropriate when there is significant change in local population size or habitat occupancy over time (Rota *et al.* 2009), as will be the case for many recent border incursions. In addition, the models may give misleading results when the efficacy of different searchers is highly heterogeneous (Fitzpatrick *et al.* 2009). Compared to experimental approaches, therefore, empirical methods are less likely to be useful for biosecurity surveillance.

**Table 1. Tools that can be used for estimating population apparency or detectability.**

Technique	Use of technique	Application	Reference	Available tools
Distance sampling	Quantifying detectability with distance	-	Thomas <i>et al.</i> (2010)	Specialized software <a href="http://www.ruwpa.st-and.ac.uk/distance/">http://www.ruwpa.st-and.ac.uk/distance/</a>
	Estimating apparency from point survey data	-	Wintle <i>et al.</i> (2004)	Software: PRESENCE, MARK, CAPTURE, SURVIV
	Estimating apparency and site occupancy	American toads, spring peepers	MacKenzie <i>et al.</i> (2002)	Software: PRESENCE <a href="http://www.proteus.co.nz/software.html">http://www.proteus.co.nz/software.html</a>
Zero-inflated binomial distribution	Estimating apparency and site occupancy	Woodland birds, forest-dwelling frogs, mound-spring invertebrates	Tyre <i>et al.</i> (2003)	R add-on to fit zero-inflated binomial distributions to biological survey data by maximum-likelihood estimation
Zero-inflated distributions	Estimating apparency and site occupancy	Mallard duck, Cherokee darter	Wenger and Freeman (2008)	R and WinBUGS code <a href="http://esapubs.org/archive/ecol/E089/166/suppl-1.htm">http://esapubs.org/archive/ecol/E089/166/suppl-1.htm</a>
	Optimal allocation of effort in detection and site occupancy studies	Amphibians in Yellowstone National Park	Bailey <i>et al.</i> (2007)	Software: GENPRES <a href="http://www.mbr-pwrc.usgs.gov/software">http://www.mbr-pwrc.usgs.gov/software</a>
	Estimating apparency and site occupancy	Breeding birds	Rota <i>et al.</i> (2009)	R code <a href="http://www3.interscience.wiley.com/journal/122681954/supinfo">http://www3.interscience.wiley.com/journal/122681954/supinfo</a>

## 4. Prioritizing species and projects

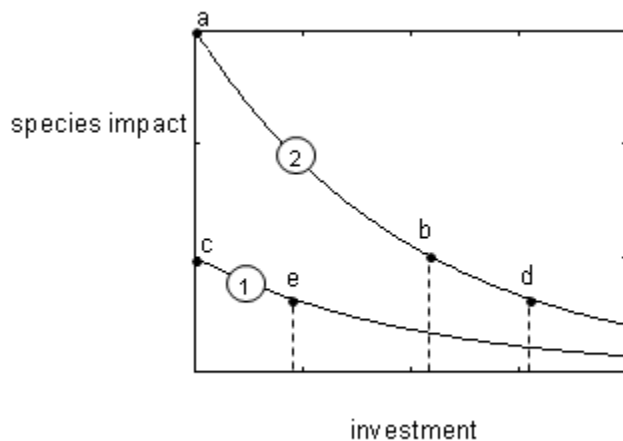
One of the first issues of biosecurity surveillance is, which species should be the subject of our survey? There is likely to be a large list of candidate species that may pose a threat to industry, human health and the environment. Some may be known to occur, while others may not be known to occur but are at some risk of being introduced. Since resources available to conduct surveillance are finite, it is desirable that transparent and repeatable procedures be used to rank and prioritize the allocation between species. Here we discuss a range of techniques that have been proposed or used for ranking species or guiding resource allocation amongst species.

In developing a list of candidate species for surveillance we must assess their likelihood of entering, establishing and spreading, and their subsequent impact on the local environment. Pathways analysis may be used to show possible methods of entry and spread of pests and diseases (see Section 5.2). Self-organizing maps are a type of neural network that have recently been trialed to identify species that are likely to establish, if introduced (Worner and Gevrey 2006; Paini *et al.* 2010). These maps compare pest assemblages from different regions around the world and rely on relatively complete lists of invasive taxa in regions being compared. When there is high similarity between two regions, pest species that are known to have established in one region are predicted to have a high likelihood of establishing if introduced to the other region.

The likelihood and consequences of their occurrence will again ideally be taken into account when surveillance and other management resources are allocated across the candidate species. A sensible objective would be to minimize the total impacts of the set of candidate pests and diseases, given finite resources. Prattley *et al.* (2007) note that in this case and in order to avoid catastrophic impacts, species with a highly uncertain impact should be targeted, as well as those with a high expected impact. Therefore, species could be scored using  $(R_i - C)\sigma_i$  (equation 8, Prattley *et al.* 2007), where  $R_i$  is the mean risk (likelihood and consequence) associated with species  $i$ ,  $\sigma_i$  is a measure of the uncertainty or variability of species  $i$ 's risk, and  $C$  is a critical risk level that should not be exceeded.

McCarthy *et al.* (in review) investigate the allocation of limited resources amongst species or projects. They expect that the impact of a pest species will be highest if nothing is invested in surveillance and other management; actual impact on the local

area is expected to decrease as investment increases. When the relationship between species impact and surveillance investment is linear or displays diminishing returns, the solution can easily be communicated graphically (see Figure 1). It is the rate at which impacts are reduced per unit of investment (the gradient or steepness of slope) that determines the cost-effectiveness of an option. The optimal strategy is therefore to 'invest in the options for which the marginal benefits (cost-effectiveness) are large, and invest to a level in each strategy such that the marginal benefits are equal'. In Figure 1, the relationship between investment and consequent species impact is plotted for hypothetical species 1 and 2. Investment in species 2 is initially more cost-effective because impact reduction per unit investment (the slope of the graph) is highest at point (a). When investment exceeds point (b), returns on investment have diminished such that investment in species 1 and species 2 is equally cost-effective - slope of the graph at point (b) equals slope of the graph at point (c). When the investment budget is exhausted, the optimal allocation invests to a level in each species such that cost-effectiveness is equal (e.g. points (d) and (e), where the graphs have the same slope).



**Figure 1. Graphical presentation of optimal investment in management amongst species to minimize overall impacts (modified from Figure 2, Hauser and McCarthy 2009).**

McCarthy *et al.* (in review) provide explicit solutions to the problem of allocating a budget amongst options when the relationship between impact and investment is linear, exponential, or hyperbolic. A spreadsheet is available to solve the optimal allocation problem using the exponential function (Hauser 2009). When the impact–investment relationship is uncertain, McCarthy *et al.* (in review) found that resources should be

invested across a broader range of options, thus avoiding reliance on the few investments thought to be highly cost-effective.

Joseph *et al.* (2009b) developed a similar scheme for prioritizing conservation projects. The authors ranked projects using the score:

$$E_i = W_i \times B_i \times \frac{S_i}{C_i} \quad (7)$$

where  $W_i$  is a weighting incorporating social, political and/or biological values for species  $i$ ;  $B_i$  is the benefit of investing in a project conserving species  $i$ ;  $S_i$  is the probability that the project is successful; and  $C_i$  is the cost of investing in the project. The highest scoring projects are selected for investment until the budget is exhausted. Here, projects are assumed to have a single intended outcome and cost, whereas the optimization approaches taken by Prattley *et al.* (2007) and McCarthy *et al.* (in review) allow project investment and consequent outcomes to vary continuously. Joseph *et al.*'s (2009b) score could be reinterpreted for biosecurity surveillance investment with  $W_i$  being the consequences of a species  $i$  infestation;  $B_i$  being the expected proportional reduction in impact brought about by detection and response;  $S_i$  being the probability that surveillance successfully detects the pest; and  $C_i$  being the cost of surveillance. In many cases,  $W_i$  will need to countenance a range of market and non-market values. Weights can be informed by revealed and stated preference techniques employed in benefit-cost analysis, or by swing weights used in multi-attribute value problems (Fischer 1995).

Multi-attribute value theory is one approach under the broad family of methods available under multi-criteria decision analysis (MCDA). MCDA can incorporate data, expert opinion and stakeholder values and its use for prioritization in biosecurity is growing. Cook and Proctor (2007) used MCDA in a workshop setting to prioritize plant pests and diseases in Western Australia, the USDA Cooperative Agricultural Pest Survey (CAPS) uses the analytic hierarchy process (AHP) to prioritize exotic plant pests for early detection surveys (see <http://ceris.purdue.edu/caps/pestprioritization/Index.htm>), and ACERA (Christian *et al.* ACERA 0809) has established a MCDA Practitioner Network, including training 41 employees of DAFF (including the three biosecurity divisions), other Australian Public Service (APS) agencies, research institutions and consultancies.

The AHP is one approach of many available in MCDA. It arranges criteria contributing to the goal into a hierarchy of independent sub-problems (e.g. Figure 2). Matrix computations are used to transform pairwise judgments of the relative importance of criteria (Saaty 1980). Each option is measured against the criteria, with its overall score being calculated as the criterion-weighted sum of these measures. This approach may be more accessible to decision makers than other MCDA techniques (or benefit-cost analysis) and is especially attractive because of its capacity to accommodate vaguely described costs and benefits. This strength, however, is also its weakness. Steele *et al.* (2009, ACERA 0607 and 0610) emphasize the predisposition of AHP to misuse. The ranking of options is dependent on the performance scoring scales, and these scales need to be carefully calibrated for consistent results. As noted in Section 3.1, the weight assigned to a criterion is a function of two things: the importance of the criterion, and the range of the consequences on that criterion (Fischer 1995, Keeney 2002). The pairwise comparisons used in AHP do not make the range of consequences salient to decision makers.



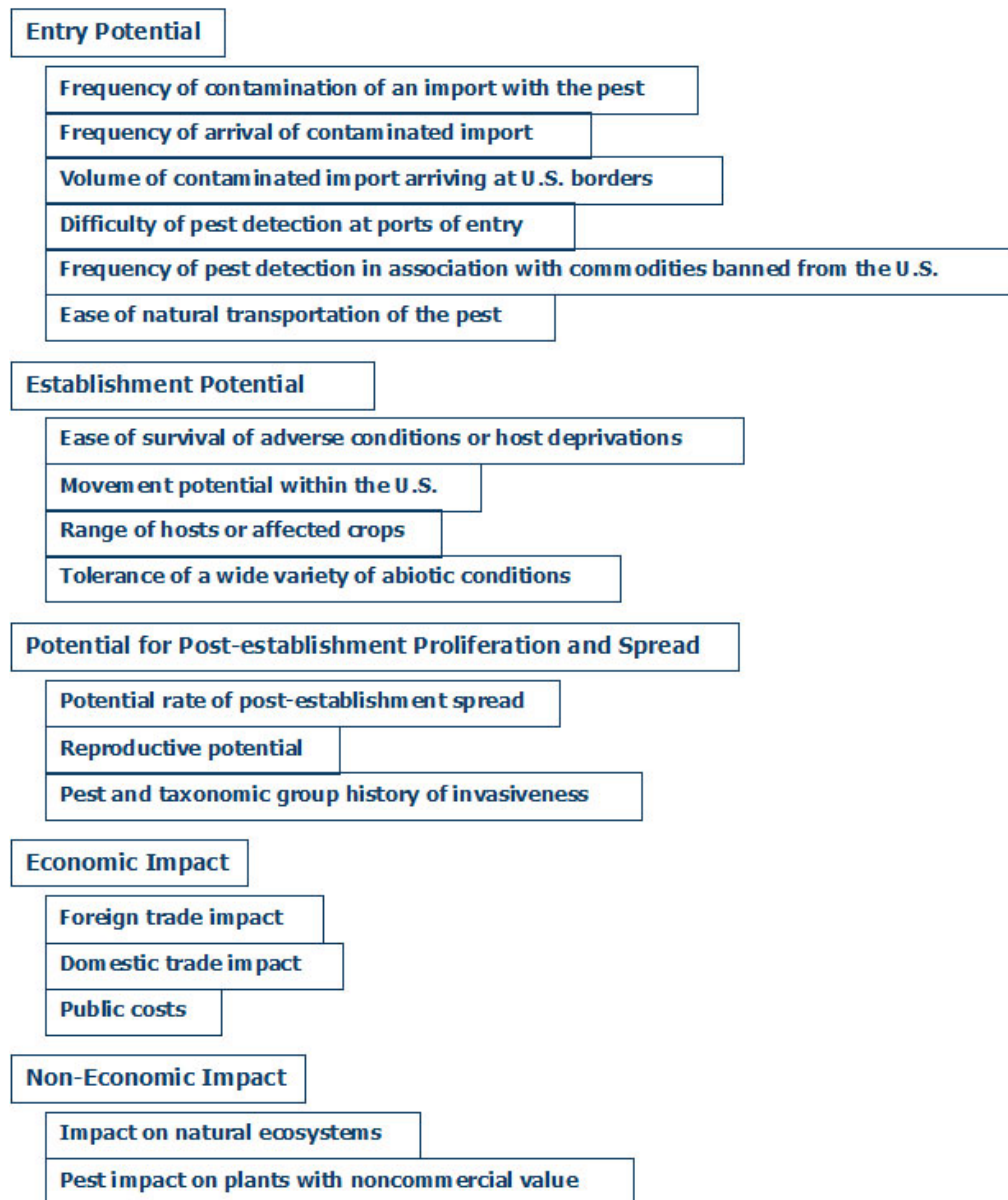


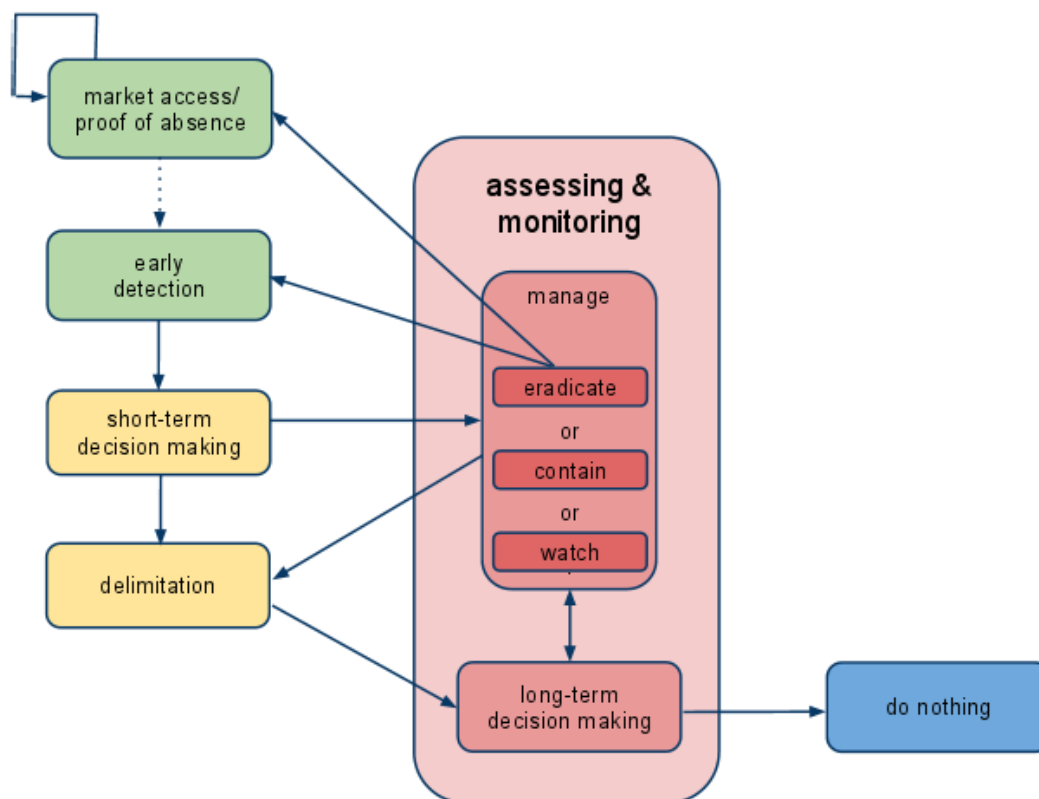
Figure 2. Hierarchy of prioritizing criteria for exotic plants pests, used by the USDA for CAPS (Source <http://ceris.purdue.edu/caps/pestprioritization/Model/htm>).



## 5. Post-border surveillance techniques for single species

In this chapter, we focus on how surveillance and other management activities can be conducted for a single pest species. We assume that the species has been identified as warranting investment, perhaps as a result of one of the prioritization processes outlined in the previous chapter.

When a particular pest or disease has been identified as a biosecurity threat warranting surveillance, the surveillance design will depend on the status of the species. We describe the phases of surveillance and infestation management in Figure 3.



**Figure 3. Conceptual diagram of the phases of surveillance and infestation management.**

When the target species is thought to be absent, surveillance may be conducted to collect evidence that this is true. Often this activity is motivated by a trade agreement that is conditioned on the absence of the species (*market access/proof of absence*). If such surveys do indeed detect the species of interest, then other actions and survey designs may be triggered.

If there is potential for the target species to arise in an area in which it is usually absent, then surveys should be designed for the purpose of *early detection*. If the species is subsequently detected, *short-term decision making* will be required to determine an appropriate response. In some cases, a protocol may have been agreed upon prior to detection (e.g. PHA 2006; 2007; AHA 2008a) and management can proceed immediately. Alternatively, or simultaneously, *delimitation* may be required to ascertain the spatial extent of the infestation before resources are allocated to its management.

After the initial response, *assessment and monitoring* are required to inform long-term decision making and management. We consider management plans of three kinds. The first, *eradication*, aims for complete removal of the target species from the infested area. Alternatively, *containment* may not remove the species entirely, but its range and thus the damages it causes are restricted in some way. Third, a species might simply be monitored with little interference (*watch*) so that managers are able to detect and respond to any future changes in the infestation's intensity and/or range. Each of these objectives requires specific surveillance activities, and these will differ depending on the objective. Furthermore, surveillance should provide information pertinent to long-term decision making, which involves re-evaluation of the long-term management goal (eradicate, contain or watch) by evaluating its consequences and feasibility, and by allocating resources to research and predictive modelling. Further delimitation surveys may also be warranted. A final management option, that of *do nothing*, may be deemed appropriate when active management is no longer possible or desirable.

In the event that eradication is successful, the objective of surveillance may revert to market access/proof of absence or to early detection, depending on probability and consequences of species re-introduction.

We now discuss surveillance and phases of management represented in Figure 3, under four sub-headings: market access; early detection; delimitation; and monitoring and assessment.

## 5.1 Market Access

Post-border surveillance for the purposes of securing or maintaining market access is undertaken to define the pest and disease status of country, or regions within a country.

Proving and maintaining pest status, including pest-free areas or areas of low pest prevalence may be necessary in the following circumstances:

- when a trading partner requires evidence that a jurisdiction, and thus its export products, are free of a particular pest or disease before it will approve the import of a commodity;
- when areas of low pest prevalence are proposed as a phytosanitary measure;
- when a jurisdiction needs to provide evidence that it is free of a quarantine pest before imposing its own restrictions on imports; and
- when an eradication programme has been completed and a declaration of freedom is made. Trading partners may require evidence that a previously infested area is now free of the pest or disease.

The vocabulary that is used to describe the relevant characteristics of systems varies among commodities. For plants, the terms *pest-free area*, *pest-free places of production* and *pest-free production sites* are used to describe particular areas, or sites within an area, that are free of a plant pest or disease (FAO 2006). For trade in animals and animal products, the term *zone* is used to describe a geographical area within a country that contains a distinct health status with respect to a specific disease(s) and the term *compartment* refers to a specific establishment that contains an animal subpopulation with a distinct health status with respect to a specific disease (OIE 2009).

For those countries that are members of the World Trade Organisation (WTO), participation in international trade in plant and animal products is governed by rules contained in the Sanitary and Phytosanitary (SPS) Agreement and the Agreement on Technical Barriers to Trade (see WTO 1998 and WTO n.d. for more details on these agreements). The SPS Agreement encourages the members of the WTO to base their sanitary measures on international standards, guidelines and recommendations, where these exist.

In line with the SPS Agreement, the International Plant Protection Convention (IPPC), an organization that protects plants by preventing the introduction and spread of plant pests, has produced a series of guidelines and standards that are recognised as the basis for phytosanitary measures applied by members of the WTO to trade in plants. These guidelines are known as International Standards for Phytosanitary Measures (ISPMs) and allow countries to analyse risks to their national plant resources and use

science-based measures to safeguard their cultivated and wild plants (IPPC n.d.). The relevant guidelines for establishing pest-free areas, surveillance, pest status and area freedom are contained, respectively, in IPSM 4, 6, 8 and 10 (FAO 1996, 1997, 1998b; and 1999).

The World Organisation for Animal Health (OIE) is recognized by the SPS Agreement as the relevant international organization responsible for recommendations affecting trade in live animals and animal products. The OIE develops rules that its member countries can use to protect themselves from the introduction of diseases and pathogens, without setting up unjustified sanitary barriers. Principles that can be used as a guide to market access negotiations and arrangements for animals and animal products are documented in *The Terrestrial Animal Health Code* (OIE 2009).

Development of an agreement that specifies particular standards to establish and maintain 'area freedom' status for specific pests and diseases occurs through negotiations between trading partners, based on guidance provided by international standards. Essentially, countries or jurisdictions are required to use science-based evidence to support their claims that a pest or disease is absent, as confirmed by surveys, in a country or region. Where possible, surveillance data should be complemented by other sources of information (e.g. scientific publications, research data, documented field observations and other non-survey data).

When establishing and maintaining area freedom is the imperative, biosecurity managers are seeking surveillance tools that allow them to answer a range of questions, similar to the following:

- how should a survey be designed in order that enough host animals/plants/sites are checked to provide confidence that if the disease is present, it would be found?
- how can survey information be used to obtain a robust estimation of likelihood that the pest/disease isn't present?
- how can information from local landowners, private industry organizations, community groups and emergency 'hotlines' be used to support area freedom?

Where surveillance is used as part of efforts to establish and maintain area freedom, evidence may be provided through either structured surveys, often enhanced by passive

surveillance, or through qualitative assessment of data from a variety of sources, usually by a panel of experts. These two approaches are discussed under the 'Prospective' and 'Retrospective' branches of the market-access mind map (see Figure 4), and we now describe each of these in more detail.

### **5.1.1 The prospective approach**

In this section we investigate how structured surveys are used to provide evidence of disease freedom. We discuss how this approach can be used to answer questions of 'How and where to look?' as well as 'How hard to look'. A mind map (see Figure 4) is used to show methods and tools that can assist in answering these questions. Statistical terminology and concepts used in this section are discussed in more detail in Section 3.2

#### **How and where to look**

The prospective approach to making claims about area freedom is based around structured surveys, with the decision on how and where to look for a particular pest or disease depending on whether the surveillance is for detection or monitoring purposes (see Figure 4: How and where to look). 'Detection surveillance' involves looking for pests and diseases that are not known to be present, and 'Delimitation and monitoring' are used to verify the characteristics of a known pest population and would be the types of surveillance undertaken under a limited number of agreements for which market access from areas of low pest prevalence is allowed (see, for example, FAO 2008).

The objective of detection surveillance may be to provide evidence that a pest or disease was not detected using a survey that had a high degree of confidence of detecting the pest, if it were present, at or above an acceptably low prevalence (i.e. close to zero). Evidence is provided through either structured population-based surveys or through structured non-random surveillance (see Figure 4 'Detection surveillance'). For some pests and diseases, regulations exist for how disease freedom should be demonstrated. Where this is the case, statistical requirements for survey design and guidelines for non-random surveillance are specified and there may be little scope for deviation from these. For example, the scrapie surveillance programme is designed so that annually there is at least a 99% probability of detecting scrapie if this disease accounted for 1% of the cases of neurological disease in sheep in Australia (AHA 2008b).

When pest- or disease-specific guidelines for a structured population-based survey have not been given, appropriate statistical practices should be followed and documented.

McMaugh (2005) gives a thorough account of the steps and relevant concepts involved in surveying for plant pests when demonstrating area freedom is the objective, and OIE (2009) and Cameron (1999) provide this information for animals. Statistical concepts for use in survey design are described in Section 3.2 and the Glossary.

A useful ‘tool’ when undertaking a structured survey is the formula that allows determination of sample size. The sample size is the number of sites that need to be surveyed in order to detect a specified proportion of pest or disease infestation with a specific level of confidence, at the design prevalence, the pre-survey estimate of the likely actual prevalence (McMaugh 2005). A typical question faced by an organization wishing to claim area freedom might be as follows:

*How many units should be sampled to ensure we can be 99% confident that a 0.2% infestation will be detected?*

In the case of a survey that is designed to detect a pest or disease for reasons of market access, the pest or disease will be absent or rare, so the following formula for determining sample size should be used:

$$n = \frac{\log(\alpha)}{\log(1 - p)} \quad (8)$$

where  $n$  is the sample size,  $p$  is the design prevalence, and  $\alpha$  is the desired confidence level, for example 0.95, subtracted from 1 (e.g. 0.05).

Where the effectiveness of a survey method is less than 100% (that is, there is a probability that an inspection can fail to detect a present pest), the formula in equation (8) needs to be modified as follows:

$$n_{adj} = \frac{n}{Se} \quad (9)$$

Where  $n_{adj}$  is the adjusted sample size and  $Se$  is the method effectiveness or sensitivity of the test. Calculations of sample size for given levels of confidence, design prevalence and method effectiveness are given in Table 2. Calculations outlined in equations (8) and (9) become difficult to apply when the number of sample sites must be selected from



a hierarchy of clustered 'levels' (i.e. paddocks, farms, districts). In this case a hierarchical or multi-stage analysis is used (Cochran 1977, Cameron and Baldock 1998a, b; Lockhart 2008).

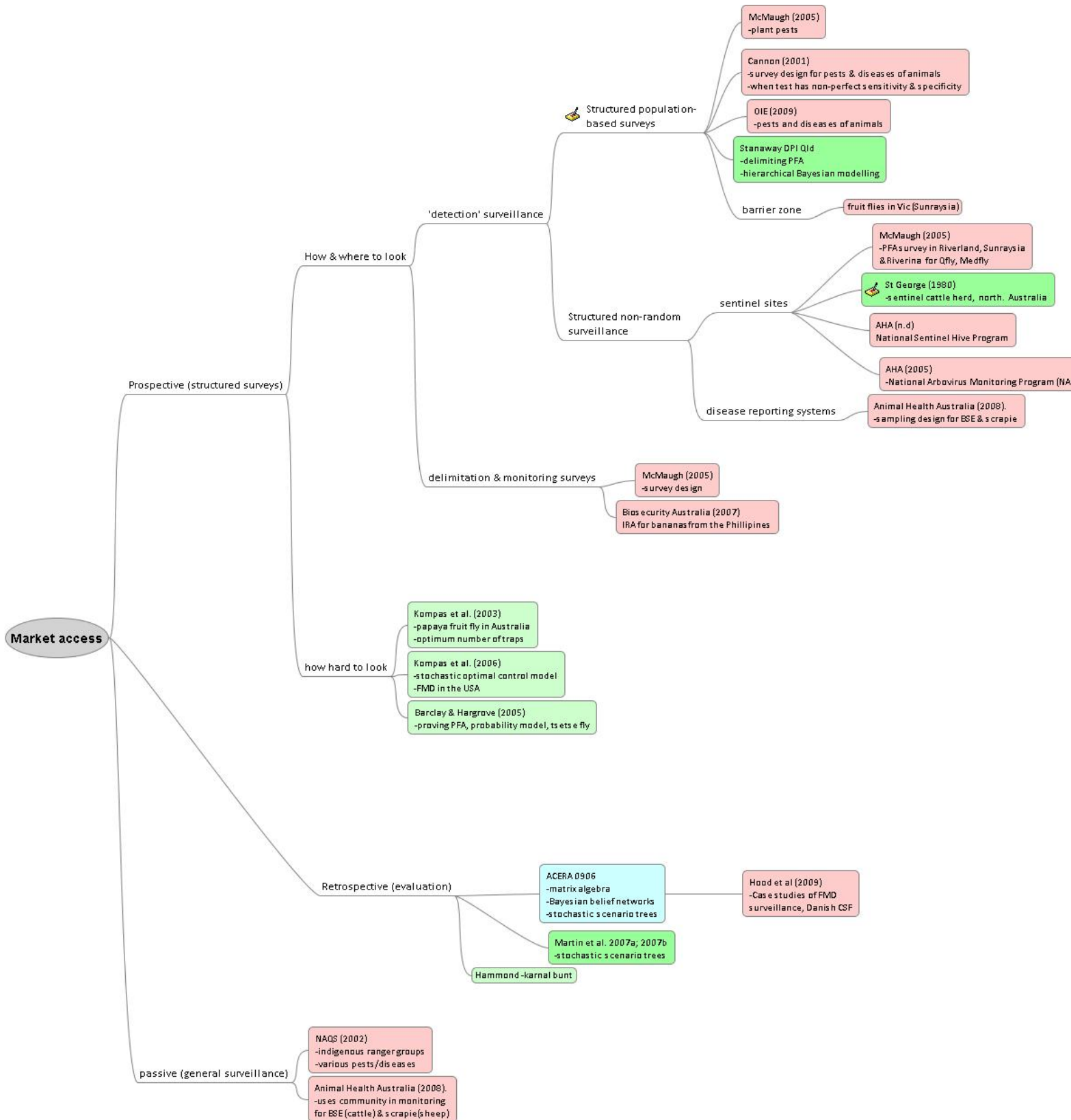
**Table 2. Calculations of sample size with method accuracy adjustments (modified from McMaugh 2005).**

Confidence	Design prevalence	Sample size	Method effectiveness	Adjusted sample size
0.95	0.01	298	0.8	373
0.95	0.02	148	0.8	185
0.99	0.01	458	0.8	573
0.99	0.02	228	0.8	285
0.95	0.001	2994	0.8	3743
0.95	0.002	1496	0.8	1870
0.99	0.001	4603	0.8	5754
0.99	0.002	2300	0.8	2875

Apart from structured population-based surveys, detection surveillance also includes structured non-random surveillance (see Section 3.2) (Figure 4: 'How and where to look: detection surveillance'). For animals, relevant sources of data that may be used to support claims of area freedom include data from reporting or notification programmes (e.g. Australia's National Animal Health Information System); control programmes/health schemes; targeted testing/screening; ante-mortem and post-mortem inspections; laboratory investigation records; biological specimen banks; sentinel units; field observations; farm production records; wildlife disease data (OIE 2009).

In Australia, results from sentinel site surveys are important in supporting claims of area freedom status for a large range of pests and diseases of plants and animals, including those of bees (Boland 2005), fruit (McMaugh 2005), and stored grain (McMaugh 2005). To maximize the chance of an early encounter with a pest or disease, sentinel sites (trees, traps or animals) are selected in locations where there is a high likelihood of a pest or disease incursions. The sentinel sites are then regularly surveyed for evidence of a pest or disease incursion. For example, under Australia's National Arbovirus Monitoring Program (NAMP) data are gathered by monitoring cattle located in sentinel herds throughout the country. Groups of at least 10 young cattle, previously unexposed to arboviral infections (Akabane, bluetongue and bovine ephemeral fever) are blood

tested at regular intervals to detect the incidence of infection with the various viruses (AHA 2005).



**Figure 4. A mind map of tools and techniques for market access (Green denotes a method described in academic literature, pink denotes a readily applicable surveillance tool and blue denotes ACERA research).**

If any type of detection surveillance mentioned above uncovers evidence of pest or disease presence, area freedom status may be revoked. Delimitation surveys are then used to define the boundaries of an infestation and should be statistically sound. The initial detection site is used as a starting point to determine how the pest or disease arrived, where it originated and to where it might have spread (McMaugh 2005). Tools that are available for delimitation surveillance are discussed in more detail in Section 5.3.

Once delimitation of the pest or disease incursion has occurred, monitoring surveys are then used to collect information on prevalence and changes in the prevalence of the pest or disease over time if eradication is to be attempted. In this context, the formula that is used for estimating sample size is:

$$n = \left( \frac{Z}{d} \right)^2 \times p \times (1 - p) \quad (10)$$

where  $Z$  represents the standard z-score derived from the normal distribution and  $d$  is the confidence interval width. Specifically, the z-score expresses the percentage of a variable's values that fall within a set interval when the variable is normally distributed – one standard deviation includes approximately 68% of the sample values and its score is 1.0, while two standard deviations include approximately 95% of the sample values and its score is 1.96 and so on (Czaja and Blair 2005). The confidence interval width indicates how close to the real population value the estimate is likely to be (Cameron 1999). It is expressed in terms of plus or minus a value that represents one-half of the range around the true value (Czaja and Blair 2005).

The design prevalence is the pre-survey estimate of the likely actual prevalence. In monitoring surveys where the pest or disease is known to be present, design prevalence can range from near zero to 100% (McMaugh 2005). Calculations of sample size for various levels of design prevalence, for a given confidence level are presented in Table 3. Note that the smaller the range is required to be around an estimate (confidence interval width), the larger the sample size needs to be.

**Table 3. Examples of sample size calculations performed with a 95% confidence level (Source: McMaugh 2005),**

Confidence interval width (%)	Design Prevalence					
	2% or 98%	5% or 95%	10% or 90%	20% or 80%	30% or 70%	50%
± 1	753	1825	3457	6147	8067	9604
± 2	188	456	864	1537	2017	2401
± 5	30	73	138	246	323	384
± 7.5	13	32	61	109	143	171
± 10	8	18	35	61	81	96
± 15	3	8	15	27	36	43
± 20	2	5	9	15	20	24

Reinstatement of area freedom status will depend on the terms of individual trading agreements, and is likely to depend on the life cycle of the pest. In some cases, trade with areas of low pest prevalence is allowed, and monitoring surveys are used to provide continued evidence of low pest prevalence (see, for example, DAFF 2004; FAO 2008).

### How hard to look

In the preceding material dealing with approaches for proving area freedom, the emphasis is on using statistically rigorous techniques to provide evidence that a particular disease or pest was not present in an area or country. Costs were not explicitly included as a factor for determining key components of survey design, although in reality resources for biosecurity surveillance are limited, so costs must play an important part in determining biosecurity surveillance levels and whether or not a surveillance programme should indeed be undertaken. Kompas and Che (2003) give the following conditions that need to be satisfied before undertaking a surveillance programme to ensure market access:

- the risk of a potential disease incursion must exist and exceed a certain probability – at low risk of disease outbreak, the threat is small and the expected benefit from surveillance is unlikely to exceed its cost;
- the potential socio-economic or environmental impacts that result from disease incursion and development should, relative to the cost of surveillance, be serious; and
- there must be a benefit from ‘early’ detection provided by surveillance – it is not necessary to carry out surveillance if early detection of the disease would not result in lower production losses and/or less costly disease management.

Kompas and Che (2003) develop a model that can be used to determine the optimum surveillance level for a pest, given likely arrival time, biological characteristics, surveillance expenditure before detection, and production losses before and after detection. The model was subsequently applied to an incursion of papaya fruit fly (PFF) in Australia (see Figure 4

‘Prospective approach: how hard to look’). The optimal level of surveillance activity is that which minimizes the sum of the expected present value of all the costs associated with pest or disease incursion over an infinite time horizon. In the case of papaya fruit fly, surveillance activity was expressed in terms of a target minimum detectable area of infestation which can be related to trapping density. Another example of this type of approach was reported in Kompas *et al.* (2006) in which the optimal level of surveillance for foot-and-mouth disease (FMD) in the United States is determined. The model is implemented in a specific computing environment called Matlab (The Mathworks 2002), so its short-term use by biosecurity managers to inform surveillance for additional pests and diseases is likely to be impeded.

### **5.1.2 The retrospective approach**

The main advantage of the survey approach is that well-established theory and methods exist, so a quantifiable probability estimate for the presence of the disease can be calculated. However, these surveys can be very expensive because large sample sizes are required to statistically prove the prevalence of the disease is at or near zero (Ausvet Animal Health Services, n.d.). We now discuss a range of techniques that allow information from non-survey sources to be used to provide evidence of area freedom. This information may come from historical records kept, for example, by veterinarians, abattoirs, farmers or plant-health experts, and thus is often ‘retrospective’ in nature.

Several recently developed techniques, based on scenario tree models, combine aspects of the structured survey approaches mentioned above with other types of surveillance data to inform the calculation of a quantitative probability estimate that can be used to support claims of freedom of disease or infection. A scenario tree is a way of representing a hierarchy of information about a system. In analysing surveillance systems, scenario tree analysis has several functions, including visualization and documentation of the logical and practical structure of the surveillance process; clarification and description of the steps involved in analysis of the surveillance system component; and definition of the interrelationships of factors affecting the probability of infection and the probability of detection (AusVet Animal Health Services n.d.). The scenario tree method is developed in Martin *et al.* (2007a) and we draw heavily on this literature in the discussion that follows.

A key part of the scenario tree method is the sensitivity of a surveillance system component where surveillance sensitivity is defined as the probability that the surveillance system will detect an infection if it were present at or above the specified design prevalence. The sensitivity of the overall surveillance system may be calculated from the sensitivities of its different components. These surveillance system components (SSC) relate to separate

sources of data, derived from distinct data collection systems or surveillance processes. This method is based on several assumptions: that all results from surveillance are negative; that if the disease is present in a country it must be present at some minimal prevalence (the design prevalence) when the surveillance is conducted (Hood *et al.* 2009); and that the specificity of the system, or method effectiveness, (the proportion of truly negative units that are correctly identified as negative by a test) is 100%.

Once sensitivities of components have been calculated they can be combined into a single estimate of the sensitivity of the whole surveillance system. Cannon (2001) and Cameron and Baldock (1998a, b) describe the approaches to use for when components are independent. The system sensitivity is founded on the hypothetical assumption that the disease or pest is present in the population and as such, is a measure of the quality of the surveillance system, rather than whether a region is actually free of a disease. The probability that a region is free of a disease, given the surveillance system has a negative outcome, can also be estimated (see Martin *et al.* 2007a).

The stochastic scenario tree model enables all available evidence about pest or disease status to be used in a transparent and quantitative manner to support claims of disease freedom. An example of its application to area freedom claims is given in Martin *et al.* (2007b) for classical swine fever (CSF) surveillance in Denmark.

Where the analysis of very complex surveillance systems leads to the construction of large scenario trees, spreadsheets or other specialist computer software must be used (e.g. @Risk (Palisade Corporation) and Poptools (Hood 2009)). The implementation of large trees can be prone to calculation error and difficult to audit by trading partners (Hood *et al.* 2009). When this is the case, Hood *et al.* (2009) show how scenario trees can be represented in a simpler manner using matrix algebra or Bayesian belief networks. These methods are applied to the FMD and Danish CSF study with the same results as were found using the method of Martin *et al.* (2007a; b).

While it may be difficult for a biosecurity manager to use the matrix method to derive the more compact scenario trees, it is likely that biosecurity managers can use readily available Bayesian network software (e.g. Netica (Norsys Software Corporation n.d.) and Smile (Decision Systems Laboratory n.d.)) to represent scenario trees and use them to support claims of pest and disease freedom.

## Summary

Post-border surveillance for the purposes of securing or maintaining market access is undertaken to demonstrate that a country, or regions within a country, are free from particular exotic pests and diseases. This evidence may be provided through either structured surveys, often enhanced by passive surveillance, or through qualitative assessment of data from a variety of sources, usually by a panel of experts. Many well-accepted tools are used for surveillance in this area, and these are listed in Table 4. Tools range from formulae to assist in survey design to stochastic scenario trees and Bayesian belief networks.

**Table 4. Surveillance tools for market access.**

Technique	Use of technique	Application	Reference	Available tools
Survey design	Evidence of area freedom when sensitivity and specificity $\neq 1$ , or sampling with replacement	Area surveys of animals	Cannon (2001); Cameron and Baldock (1998a); Cameron and Baldock (1998b); Cannon and Roe (1982)	Formulae FreeCalcV2 – <a href="http://www.ausvet.com.au/content.php?page=software#freecalc">http://www.ausvet.com.au/content.php?page=software#freecalc</a> Epi Tools Suite - <a href="http://www.ausvet.com.au/content.php?page=epitools">http://www.ausvet.com.au/content.php?page=epitools</a>
Bayesian belief networks	Evidence of area freedom in multiple component systems	FMD Danish CSF	Hood <i>et al.</i> (2009)	Netica, GeNie, Smile and others
Stochastic scenario tree models	Evidence of area freedom	Classical swine fever, Denmark Survey of an invertebrate, Barrow Island, WA	Martin <i>et al.</i> (2007a, b) Barrett <i>et al.</i> (2009) Jarrad <i>et al.</i> (2010)	Procedure and formulae @Risk, PopTools, AusVet Freedom software at <a href="http://freedom.ausvet.com.au/">http://freedom.ausvet.com.au/</a>
Survey design	To provide evidence of freedom from a disease	Various case studies presented	McMaugh (2005)	Formulae

## 5.2 Early Detection

When surveillance is undertaken for early detection, the aim is to find invasions of new pests and diseases early enough to enable effective and efficient management (eradication and/or containment). There is a trade-off between using resources to find incursions early, and using resources to manage the incursions once detected: the earlier an incursion is detected the lower will be the resources required for subsequent management compared to finding the initial incursion when it has spread further. Surveillance for early detection is particularly challenging because there is often little or no information available about where, when and how a new target species will arrive in a country or region (Kean *et al.* 2008), but the expectation is that a particular pest or disease will arrive eventually.



Early-detection surveillance systems can be expensive for pest-management authorities to maintain, especially when they involve repeat surveys over large, heterogeneous landscapes, so it is important to invest resources where they will be most beneficial. This aspect of early detection is discussed in Section 6: Decision making.

We divide our discussion of surveillance tools for early detection into three sub-sections: where to look, how to look and how hard to look. We conclude by presenting a list of available early-detection tools.

## **Where to look**

Much of the research in the area of early-detection surveillance is aimed at improving knowledge on where and when to expect the arrival of an invasive species. This knowledge is then used to inform active surveillance undertaken by pest management agencies. Thomas *et al.* (2007) and Sindel *et al.* (2008) use *pathways analysis* to show entry and spread of weeds in Victoria and Australia, respectively, where pathways represent any means that lead to the potential entry and spread of pests and diseases. Sindel *et al.* (2008) used the literature to identify 17 pathways of weed spread, and then surveyed weeds professionals, asking them to rate and discuss the efficiency, importance and regulatory effectiveness of each pathway. Thomas *et al.* (2007) combined *risk analysis* with pathways analysis to enable ranking of the relative risk of weed-spread pathways in Victoria so that resources for surveillance could be prioritized accordingly. The need to prioritize resources for surveillance according to riskiness of pathways was reflected in Recommendations 45 and 52 of the Beale Review (Beale *et al.* 2008).<sup>1</sup> The criteria developed by Thomas *et al.*

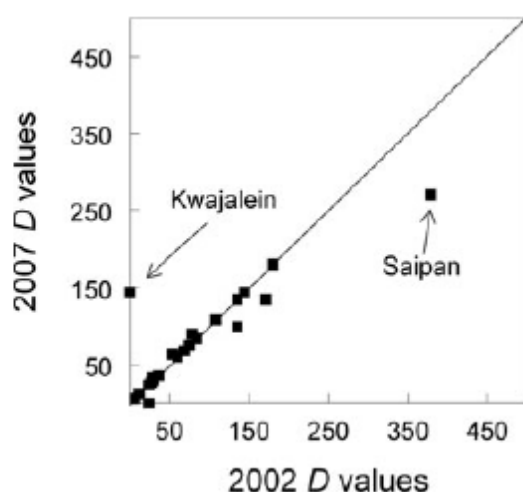
---

<sup>1</sup> Recommendation 45: 'The National Biosecurity Authority, in consultation with relevant stakeholders and the Biosecurity Advisory council, should develop a list of national priority pests and diseases, with their respective pathways, on the basis of the likelihood of incursion and the consequences for businesses, human health and the environment. The list should be used to prioritise the review and development of comprehensive biosecurity risk management plans across the biosecurity continuum.'

Recommendation 52: 'The National Biosecurity Authority should undertake a continuing programme of analysis of risk pathways using data collected from pre-border intelligence and border inspections at control points along the continuum. The results from this analysis should be used to update risk management strategies and measures.'

(2007) for their risk assessment framework were weighted using an analytical hierarchical process (AHP), with weights determined using a software package called Catchment Decision Assistant ©. This software helps users to structure a problem into a hierarchy of criteria, then systematically rates and weights the relative importance of each criterion as it contributes to a particular issue. It also connects the decision making framework to geographic information systems. The process of risk mapping using AHP was also applied by Barrett *et al.* (2009) to determine likely entry points, and thus where surveillance should be focused, for an invasive ant (*Pheidole megacephala*) on Barrow Island, Western Australia.

Perry and Vice (2009) used a simple mathematical model to identify islands in the Pacific that were at high risk of brown tree snake entry and establishment as a result of transport and cargo movements from Guam, where this species is a serious invader. The authors defined the risk of brown tree snake incursion ( $D$ ) as a function of how frequently snakes arrive and the likelihood of an arriving snake establishing a population. Changes in  $D$  over time occurred as a result of changes in transportation parameters (frequency of arrivals, method of transport) or establishment of the invader on additional islands. Information on the risk of establishment could be used to inform interdiction efforts events on Pacific islands where the threat of snake arrival is determined to have changed. Values of  $D$  changed little between 2002 and 2007 for most islands (see Figure 5), but there was an increase in the risk for Kwajalein, which did not receive cargo from Guam in 2002, and a slight reduction in the predicted risk for Saipan due to changes in flights between Guam and that island (Perry and Vice 2009).



**Figure 5. Comparison of risk estimates ( $D$ ) for 2002 and 2007 data for the same localities. The diagonal line shows the expected placement if no change in risk had occurred over time (Source: Perry and Vice 2009, Figure 3).**

Methods for determining where to look for a pest or disease are often taxon-specific. For example, Meats (1998) showed how Cartesian methods, where sentinel traps are located on a rectangular grid, can be used to estimate the location of epicentres of fruit flies caught in the traps. Using this method, knowledge of map coordinates of the traps allows the origin of the fruit flies to be calculated – the origin is most likely to be at or near the mean coordinate, when the mean is calculated from the coordinates of each fly caught (Meats 1998).

## How to look

Once the locations of early detection efforts have been determined, the question becomes, 'how should we look?' for the invasives. Methods are usually a combination of active surveillance that is undertaken by pest-management agencies through active (and targeted) *surveys*; and *passive surveillance*, where members of the community report possible new incursions to the pest-management agency (see Figure 6: survey/sampling technique and passive surveillance).

In principle, survey techniques for early detection are the same as those discussed in the context of market access (Section 5.1), but without any immediate trade imperative or prescribed survey protocol that insists on a particular testing intensity or density of traps. To ensure that survey results are meaningful it is important that statistically appropriate *survey design* and *sampling techniques* be used (see Sections 3.2 and 5.1 for more details). Rew *et al.* (2006) discuss the applicability of various sampling methods, evaluating seven of these (one biased and six unbiased) for simulated populations of an invasive plant (see Figure 6: How often to look: survey/sampling technique'). MacKenzie and Royle (2005) provide a useful discussion on survey design and selection of sampling sites when attempting to describe the level of occupancy of a region or landscape. Barrett *et al.* (2009) and Jarrad *et al.* (2010) present statistical designs for ants and rats on Barrow Island, and argue that the spatial and temporal placement of the surveillance system units may be carried out by skilled operational staff giving consideration to occurrence risk factors at the local scale.

In terms of tools that may be applied for early detection, Barrett *et al.* (2009) provide a method for calculating the number of surveillance system (SS) units that would be required to detect non-indigenous species, with a given statistical power, and a specified number of independent individuals. This system can be comprised of multiple SS components (SSCs) such as structured surveys, trapping methods, incidental sightings by non-experts, and any other detection method for which sensitivity and footprint are known or can be reasonably estimated. The number of units of each SSC in the system can then be optimised for broad

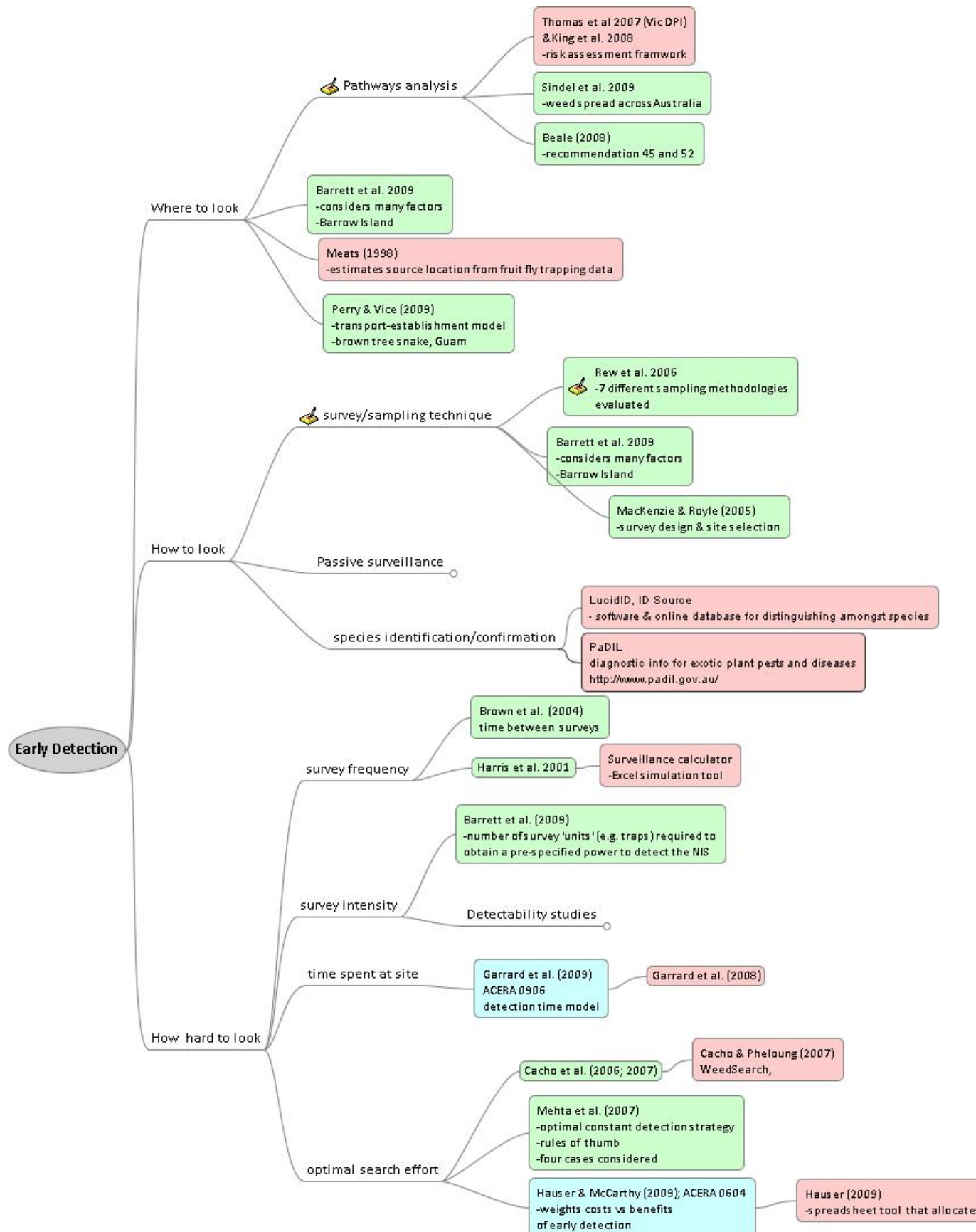
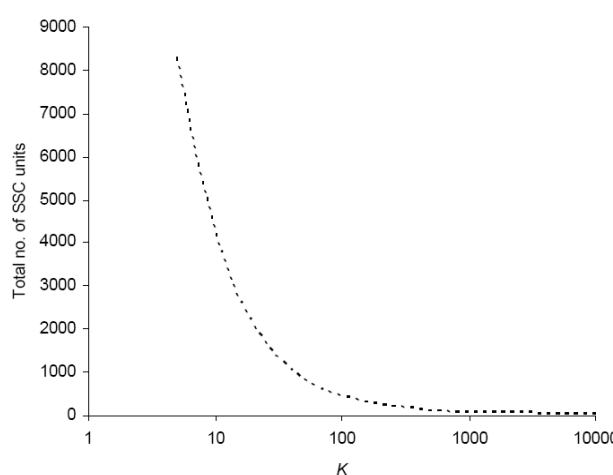


Figure 6. A mind map of surveillance tools for early detection. (Green denotes a method described in academic literature, pink denotes a readily applicable surveillance tool and blue denotes ACERA research).

cost factors such as financial cost, technological limits and environmental impact. The methodology was applied to a non-indigenous invertebrate pest, the big-headed ant (*Pheidole megacephala*) on Barrow Island (Barrett *et al.* 2009) and extended to a non-indigenous vertebrate pest, the black rat (*Rattus rattus*) on this same island (Jarrad *et al.* 2010), acting as exemplars for species with similar invasion biology. The number of SSC units required to detect a population size of 10 black rats ( $K=10$ ) (a population thought large enough to be detected but small enough to be eradicated without significant environmental consequences and costs) was found to be 4166, substantially more than would be required for larger values of  $K$  (Figure 5). The choice of  $K$  is based on the invasion biology of the species, and the risk-based issue of how soon after invasion the species must be detected.



**Figure 7. The effect of changing the tolerable population size ( $K$ ) on the number of required SSC units for *Rattus rattus*, for a power of 0.8 (Source: Jarrad *et al.* 2010, Figure 3).**

Early detection of pests and diseases through passive surveillance has often been the method by which an invader is first recognized in a country or region. For example, members of the public were responsible for initial detections of red imported fire ant in Brisbane, Queensland (Jennings 2004); mango leaf gall midge on Horn Island, Queensland (Beale *et al.* 2008); and a long list of invasives in New Zealand, including painted apple moth, Dutch elm disease, red imported fire ant and didymo (Helström 2008). Ways of using information from the community range from emergency 'hotlines' (Froud *et al.* 2008), to using the skills of farmers, private veterinarians and specialized pest-detection groups such as those of the National Plant Diagnostic Network in the USA and 'Weedspotters' in Victoria (DPI 2008) and Queensland (Queensland Government n.d.). This type of surveillance information can be combined with other surveillance data using scenario trees (Martin *et al.* 2007a) and can be incorporated into new designs or analysed after the fact using the Barrow Island method (Barrett *et al.* 2009, Jarrad *et al.* 2010).

Once detection of a pest or disease is suspected, confirmation of the detection becomes necessary. Software systems are now available to provide rapid diagnostic information. Examples include Lucid (CBIT n.d.) and the Pest and Disease Images Library (PaDILsee <http://www.padil.gov.au/>).

### **How hard to look**

Once decisions have been made about where and how to look for an invasive pest or disease an additional question becomes ‘how hard to look?’ Methods and tools have been developed to answer this in several ways: in terms of survey frequency; survey intensity; time spent at a site; and the optimal search effort that should be expended in the detection process.

Brown *et al.* (2004) and Harris *et al.* (2001) tackle the issue of search frequency – time between surveys – when the ability to detect a species improves over time due to its increased spread (see Figure 6: how hard to look: survey frequency). Recommendations for weed-surveillance intervals are given for a range of weeds in a range of habitat types, and depend on the rate of weed growth, the ability to detect a weed, and the cost of controlling the weed. The model was made available as a spreadsheet, although the authors are unable to verify details of where it may be obtained.

Survey intensity – the number of survey units (e.g. traps, nets) required – is related to detectability of the pest or disease and has been investigated for a range of pests and diseases (see Section 3.3). Barrett *et al.* (2009) provide a tool for choosing survey intensity to detect non-indigenous species, based on the power of detection (the probability of detection, given presence). To use this tool, information is required on the types of survey methods (SSCs) to be included in the system, the risk of pest or disease presence in each zone, the design population size for detection, the probability of detection using each survey method, fraction of the target area surveyed by each method and cost of each survey method.

The optimal search effort that should be applied to detecting a pest or disease has been investigated with a range of models. In the simulation model of Cacho *et al.* (2006; 2007) search theory concepts are incorporated into a population model, and the costs of search and control are calculated as functions of the amount of search effort (the decision variable). The model has subsequently been applied to a weed in the Wet Tropics of Australia to determine the effect of changing search effort of eradication feasibility (Hester *et al.* 2010). A user-friendly spreadsheet model based on Cacho *et al.* (2006), Weed Search (Cacho and

Pheloung 2007) is freely available for exploring the effect of changing levels of search effort (see Table 5).

Mehta *et al.* (2007) and Hauser and McCarthy (2009, ACERA 0604) provide other examples of models that can be used to explore optimal search effort. Hauser and McCarthy (2009) used an occupancy model, a detection model and an economic analysis to identify how surveillance effort should be allocated across a heterogeneous landscape. Two surveillance objectives were considered:

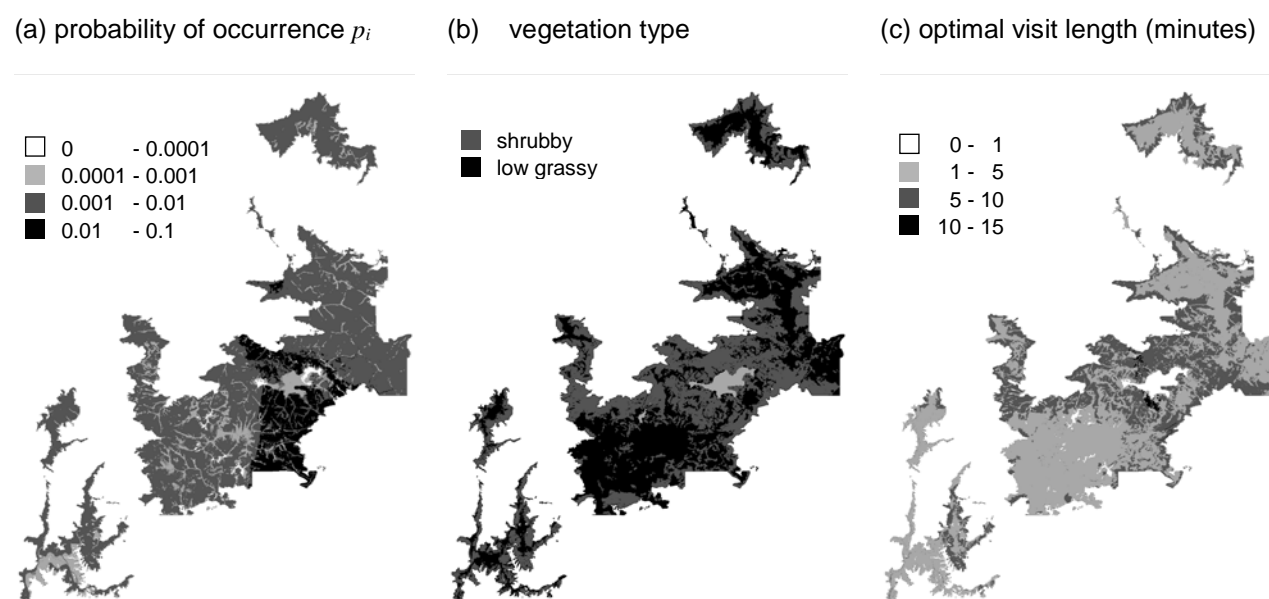
- optimally trading the costs of surveillance against the benefits of early detections (benefit-cost analysis), and
- optimally distributed a surveillance budget amongst sites to maximize the benefits of early detection (cost-effectiveness analysis).

Hauser and McCarthy (2009) found that for both objectives, sites can be optimally prioritized using a score that is the product of the probability of pest presence, the rate of detection at the site, and the benefits of early detection for the site. The optimal surveillance effort can be implemented using a readily available spreadsheet tool (Hauser 2009). Figure 8 demonstrates the allocation method for ground searches of orange hawkweed on the Bogong High Plains of Victoria, Australia. Figure 8a presents the probability of orange hawkweed occurrence (from Williams *et al.* 2008); Figure 8b shows vegetation type, where shrubby areas are more difficult to search than low grassy areas; and Figure 8c optimal visit length per site (minutes), assuming that a detection failure ultimately costs 10 times more than successful early detection and treatment.

Garrard *et al.* (2009) focus on detection time in their work on designing optimal surveillance strategies for early detection. Models of detection time are presented for two highly invasive weeds, serrated tussock (*Nassella trichotoma*) and Chilean needle grass (*Nassella neesiana*), based on environmental and observer variables. They also discuss a trait-based model of plant detection time that may be used to provide estimates of detectability where no species-specific detection model exists (Garrard *et al.* 2008; 2009). Detectability curves show that under favourable survey conditions, duration of surveys should be 55 minutes/ha for Chilean needle grass and 35 minutes/ha for serrated tussock, in order to be 80% certain that a survey of a site will return a detection if the species is present (Garrard *et al.* 2009). This information is useful in prioritizing surveillance activities and the amount of resources to allocate to surveillance (see Section 6). Computer code for implementing the method in the Bayesian freeware WinBUGS is provided in Garrard *et al.* (2008).







**Figure 8. Application of Hauser and McCarthy's (2009) surveillance allocation model for ground searches of orange hawkweed on the Bogong High Plains.**

## Summary

When surveillance is undertaken for early detection, the aim is to find invasions of new pests and diseases early enough to enable effective and efficient management (eradication and/or containment). This can be difficult where there is little or no information available about where, when and how a new target species will arrive in a country or region. The range of readily deployable tools that can assist in early-detection surveillance is given in Table 5. Tools range from qualitative analysis techniques through to simulation models and scenario trees. Two of these tools - WeedSearch and the spreadsheet model of Hauser (2009)- are readily applicable because the information they require is readily available and computing time for simulations is minimal.

**Table 5. Surveillance tools for early detection.**

Technique	Use of technique	Application	Reference	Available tools
Scenario trees	For designing multi-element surveillance systems to a specified statistical power	Survey of an invertebrate, Barrow Island, WA	Barrett <i>et al.</i> (2009) Jarrad <i>et al.</i> (2010)	Formulae
Simulation model	Determines eradication feasibility for various search efforts	4 hypothetical weed scenarios	Cacho and Pheloung (2007)	Weed Search <a href="http://www-personal.une.edu.au/~ocacho/weedsearch.htm">http://www-personal.une.edu.au/~ocacho/weedsearch.htm</a>
Spatial model of detection and treatment	Determines effort allocation across landscape; costs vs benefits of early detection	Orange hawkweed, Vic	Hauser (2009)	Spreadsheet model email request to : chauser@unimelb.edu.au
Qualitative analysis	Develops a model for community based detection	Weed detection network in Australia	DPI (2008)	Template
Modified failure-time model	Measures time to detection	Two invasive grass species, threatened native plant, Vic	Garrard <i>et al.</i> (2008; 2009)	Computer code

### 5.3 Delimitation

The aim of surveillance undertaken for delimitation is to establish the boundaries of a known incursion of a pest or disease. Delimitation for most invasive pests and diseases is a difficult process, and the range of methods is limited. Leung *et al.* (2010) conceptualize delimitation as a trade-off between the probability of escape and wasted effort: if the quarantined area in which searching takes place is too small, then the range of the invader will not be enclosed, and escape may occur, but if the quarantined area is too large then there will be wasted effort because searching will take place in areas that have not yet been reached by the invader.

Despite the paucity of tools and theory supporting delimitation, this process is routinely undertaken as part of invasive species management. Surveillance to delimit an incursion usually occurs after an initial detection of a pest or disease and before a particular management strategy is initiated. In some industries, however, biosecurity plans exist that detail pre-emptive actions to manage incursions immediately after initial detection, and management is carried out simultaneously with delimitation. This is often the case where there is a trade imperative to re-establish area freedom status as quickly as possible (for examples, see PHA 2006; 2007). Delimitation should be undertaken as quickly as possible,

because the invasive species continues to spread as searching is taking place, increasing the probability of escape, the extent of the invasion and the ultimate effort required to manage the invasion (Leung *et al.* 2010).

We divide our discussion of delimitation tools into three sub-sections: where to look, how to look, and how to achieve delimitation. We conclude this section by presenting a list of available delimitation tools.

### **Where to look**

In this section we analyze the problem of determining the locations at which delimitation efforts should be focused once an incursion has been detected (see Figure 9: 'Where to look'). An understanding of likely means of introduction as well as the method, amount and direction of dispersal from both the known infestation and from the original site of incursion, is almost always valuable, and usually crucial. The initial detection site should be used as a starting point for gathering the required information, although this site will not necessarily be the initial point of introduction.

*Trace-back and trace-forward* techniques, combined with *pathways analysis* can be used to gather information on introduction and spread (see Figure 9: Where to look: trace-forward trace-back and pathways analysis). Trace-back enquiries are used to locate the likely original site of introduction, and if this is successful, trace-forward activities will then help to locate areas, objects or animals that might be infested and will need to be surveyed. For example, the Victorian Government recently traced the location of Mexican feather grass (MFG) using credit card sales information from nurseries in Victoria – during early 2008 large numbers of MFG plants were sold by nurseries, and planted in private gardens across the state (DPI 2009b; A Dodd, pers. comm.). Australia's National Livestock Information System (NLIS) and New Zealand's proposed National Animal Identification and Tracing (NAIT) project are examples of formal tracing schemes that could be used in the context of delimiting an incursion of a pest or disease of livestock (MLA n.d; MAFBNZ 2009).

Pathway analysis (see Section 5.2) can be used to investigate how the entry of a pest or disease into a country or region occurred, and give additional information about possible dispersal mechanisms. Pathways analysis is often used in conjunction with trace-forward and trace-back techniques in delimitation surveillance, for example, as in the recent delimitation of Siam weed (*Chromolaena odorata*) that took place in Queensland (QNRM 2006). Pathways analysis was used to identify probable sources of new incursions from outside Australia (e.g. tourists, seed imports, timber imports) and high risk pathways along which

Siam weed could be moved once inside the country (e.g stock, earthmoving machinery, bushwalkers). Pathways identified as high risk became the basis of trace-forward investigations.

When there has been time to establish the habitat preferences of an invasive species, *dispersal* and *habitat suitability models* can be used to identify areas prone to invasion (see Figure 9: Where to look, dispersal and habitat suitability models). Hastings *et al.* (2005) review and synthesize recent developments in the study of the spread of invasive species and give examples where models have been tested with data.

Habitat suitability models define the habitat types that have been invaded, and can subsequently be used to indicate which similar areas might also harbour the invader, or are more likely to face the most immediate threat of being invaded. Elith and Leathwick (2009) provide a review of habitat models in terms of their history, cross-disciplinary features and diverse uses, including their use as a tool for predicting the suitability of new environments for a given species. Václavík and Meentemeyer (2009) and Smolik *et al.* (2010) also provide useful information on modelling the spread of invasive species.

We describe only a small sample of habitat suitability models that could be used in a delimitation context in Figure 9. Shaffi *et al.* (2003) used a non-linear regression model, based on landscape characteristics of elevation, slope and aspect to accurately predict the incidence of yellow star-thistle in north-central Idaho, USA. Williams *et al.* (2008) and Fox *et al.* (2009) provide examples of combining dispersal models with information on habitat suitability to predict weed occurrence across a landscape. Williams *et al.* (2008) used habitat suitability indices, developed from information on disturbance, site wetness and vegetation community parameters, to predict those areas of the Bogong High Plains in Victoria that would be highly suitable for the arrival and establishment of orange hawkweed. These indices were constructed from literature review and from expert opinion on the current distribution of this weed in Australia, and were combined with a dispersal model that quantified the likelihood of seed arriving at particular distances from the source plant. The model was not able to be evaluated using field searching, because despite extensive searching in areas predicted to be highly suitable, no orange hawkweed plants were detected. The model, however, was able to predict the location of orange hawkweed populations recorded in late 2003 from populations recorded prior to autumn 2000 (Williams *et al.* 2008).

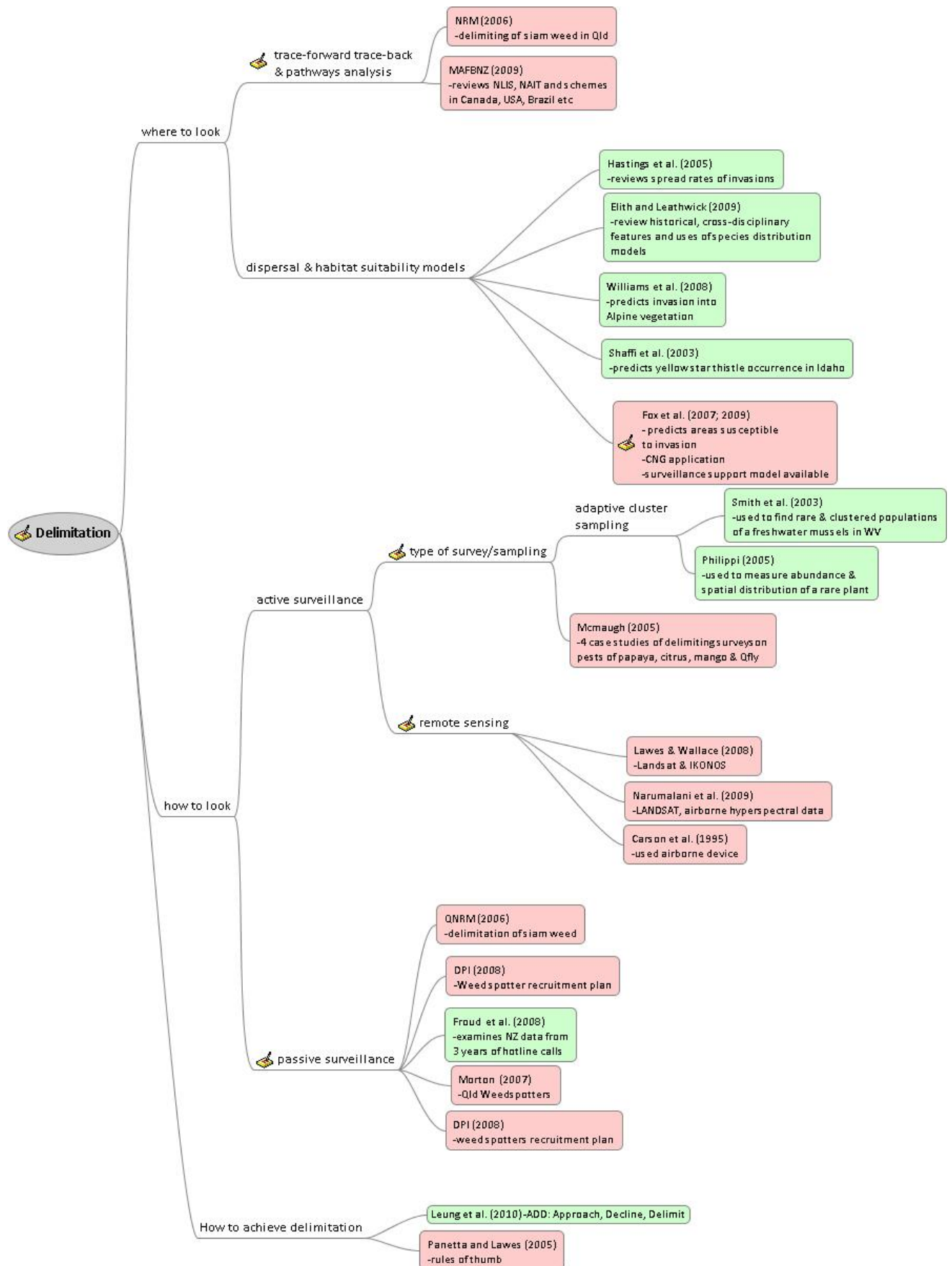
Fox *et al.* (2009) report the development of a surveillance support tool that can be used to assist in the delimitation and management of weed incursions. The tool is developed using

Python functions (Python being a computer programming language) that can be parameterized from an ArcGIS user interface and used to simulate invasions of plants across differing landscapes through a range of dispersal mechanisms. In the study, the tool was used to evaluate the effectiveness of different surveillance techniques for Chilean needle grass in south-eastern Queensland. Surveillance strategies tested included systematic sampling; random sampling; habitat-based sampling; seek-and-destroy; and adaptive versions of each. Several rules of thumb emerged from the application of the tool to Chilean needle grass:

- for new incursions in a fragmented habitat mosaic, habitat preference should be identified, and suitable habitat should be targeted in surveillance efforts;
- for new incursions in a continuous habitat mosaic, dispersal vectors should be identified and areas vulnerable to dispersal from these vectors should be targeted;
- adaptive surveillance (learning from previous year) outperforms non-adaptive surveillance; and
- the maximum expected dispersal distance should be used when choosing a search radius for adaptive surveillance (Fox *et al.* 2009).

It should be noted, however, that resource constraints were not taken into account in this study which may affect conclusions such as (iv).

Information on habitat preferences and models of dispersal for new incursions are often sparse, and there may be little more to inform search strategies than the information gained from tracing activities. When this is the case, Panetta and Lawes (2005) suggest that the surveillance strategy should involve systematic, intensive surveys in the local vicinity of known occurrences, in conjunction with surveys in other areas that are selected based on putative dispersal behaviour and potential pathways of spread. Schmidt *et al.* (2010) compared the value of searching for red imported fire ants using a habitat suitability model with a strategy of proximity searching (searching a predetermined radius around each detected nest) in terms of number of nests detected. A consistently higher proportion of nests were found using the habitat suitability model over a range of search efforts, in some cases the detection rate was almost twice as high as that which occurred using the proximity search.



**Figure 9. A mind map of surveillance tools for delimitation (Green denotes a method described in academic literature and pink denotes a readily applicable surveillance tool).**

## How to look

In the process of delimiting a pest or disease incursion, surveillance may be undertaken actively, under the auspices of a pest-management authority, or passively, such as accepting reports from members of the public of encounters with pests (see Figure 9: How to look).

*Active surveillance* involves deliberate searching for the pest or disease through surveys. Principles of survey design for delimitation are outlined in McMaugh (2005), and are similar to those discussed in some detail in Section 5.1 on market access. For low-density pests that exhibit a clustered distribution, abundance can be estimated using adaptive cluster sampling (see Section 3.2). Spatial clustering implies that once one pest is found, nearby locations are much more likely than random locations to also have the pest (Philippi 2005). Smith *et al.* (2003) demonstrated adaptive cluster sampling for rare (but not invasive) mussel species and Philippi (2005) used this technique to determine the abundance and spatial distribution of a rare plant.

Conventional surveys may be impractical for determining the extent of an incursion when large areas are involved or when terrain impedes location access, due to the high costs of searching. *Remote sensing* (aerial photography, multispectral airborne sensors, satellite imagery) may be used as a surveillance tool for delimitation in these situations (see Figure 9: How to look: remote sensing). Remote sensing has been used to estimate the extent of prickly acacia across 29 000 km<sup>2</sup> of the Mitchell grasslands of northern Australia (Lawes and Wallace 2008), to quantify and map invasive species on a floodplain in Nebraska (Narumalani *et al.* 2009), and for quick and economical detection of small, disjunct areas of yellow hawkweed (*Hieracium pratense*) over large areas in northern Idaho (Carson *et al.* 1995).

*Passive surveillance*, in which members of the community report possible sightings of particular pests and diseases, can assist in directly estimating the extent of an incursion or identifying priority areas for subsequent active follow-up (see Figure 9: How to look: passive surveillance). The community is usually made aware of incursions through public awareness campaigns and may be offered a monetary incentive to report possible detections (e.g. QDPIF 2008). Cacho *et al.* (2010) explored the effect of increasing detections through passive surveillance on the success of an eradication program. The authors found that when improvements in passive surveillance occurred, the area invaded by a pest could be reduced to eradicable levels. Passive surveillance was a key component of the recent attempt to delimit Siam weed in Queensland, where various stakeholder groups were targeted through paid television advertising, direct mail-outs, letterbox drops, public relations events, and

press and radio coverage (QNRM 2006). Additional examples of passive surveillance are discussed in Section 5.2 (on early detection).

### How to achieve delimitation

Previous sections have discussed methods that can be used to become better informed about the invader and the invasion, but how do we know that delimitation has been achieved; that we know the full extent of the incursion? Panetta and Lawes (2005) suggest two rules of thumb for evaluating progress towards delimitation:

- (i) that the cumulative area of infestation becomes stable over time; and
- (ii) that there is a decrease in the detection ratio (the total area of infestation newly discovered, divided by the annual total area searched) over time.

Leung *et al.* (2010) present what appears to be the only published model that provides a method for rapidly delimiting the invasion boundary of a spreading organism. They develop a delimitation algorithm for circumstances when there is no knowledge about the initial invasion site or the direction and extent of dispersal, but the site of the initial detection is known. The authors test what they term the Approach-Delimit-Delimit (ADD) procedure:

- (i) **A**pproach (search) towards the boundary;
- (ii) as the edge of the invasion is approached, measure the **D**ecline in density of occurrences; and
- (iii) use the rate of decline to **D**elimit the invasion.

The approach is based on probability and sampling theory and uses data assembled from the search process to draw inferences about the extent of the invasion, which is theorized to exhibit declining density as movement towards the boundary occurs. The best estimate of the ultimate extent of the infestation is thus estimated in a probabilistic sense (Leung *et al.* 2010).

While application of the ADD algorithm was shown to work well in many of the simulated landscape and invasion pattern it was applied to, the authors acknowledge that challenges remain. Among them are (i) that there will often be insufficient data to build the ADD algorithm and when this is the case alternative delimitation strategies will need to be found; (ii) that the algorithm performs sub-optimally when very small numbers of sites are occupied (1-5%); and (iii) knowledge about the epicentre of the invasion strongly affected the degree



of overestimation (Leung *et al.* 2010). Furthermore, it is unclear how the ADD algorithm would apply in situations where the invasion does not progress outwards as a smooth front from the centre of an invasion. Nevertheless the ADD algorithm is a useful starting point in the development of a tool to assist in achieving delimitation.

## Summary

The aim of surveillance undertaken for delimitation is to establish the boundaries of a known incursion of a pest or disease. This has proven a difficult task due to lack of information about the site and date of the initial introduction(s) and dispersal characteristics. Delimitation is considered a fundamental prerequisite to eradication (Panetta and Lawes 2005) but is rarely achieved before eradication programmes are initiated (Panetta 2009).

In Table 6 we present the few tools available that can be used to undertake delimitation surveillance. While many more techniques have been discussed, only two have been identified as providing tools that can be readily used to assist in achieving the goal of delimitation. To the best of our knowledge no readily usable tools specifically for the delimitation task exist, although the method developed by Leung *et al.* (2010) shows promise in this regard.

**Table 6. Surveillance tools for delimitation.**

Technique	Use of technique	Application	Reference	Available tools
Simulation model	Simulate dispersal; evaluate surveillance and management	Weeds. Applied to Chilean needle grass	Fox <i>et al.</i> (2009)	Surveillance support model: <a href="http://www.uq.edu.au/lir/weedtoolbox">http://www.uq.edu.au/lir/weedtoolbox</a>
Trace-forward, pathways analysis	To inform delimitation surveys	Siam weed, Qld.	QNRM (2006)	Practical example

## 5.4 Monitoring

The fourth purpose of post-border surveillance is to monitor the progress of existing infestation management programmes. The survey design and data collected should be chosen to serve the objectives of the programme. We classify the objective of a programme broadly as eradication, containment or watching without interference (see Figure 3). Identifying which objective is most suitable for any particular case is discussed in long-term decision making (Section 6.2). We concentrate here on the tools that may assist in the planning and design of monitoring surveillance (see Figure 10).

When the pest is known to occur across the landscape, active surveillance can be useful for continued delimitation (see Section 5.3), identifying sites that require control effort, and observing changes in population density at known sites of infestation. Targeted surveillance designs that are useful for early detection (Section 5.2) will also be efficient for prioritizing control effort. Approaches that consider only pest presence/absence (e.g. Hauser and McCarthy 2009) may not offer efficient designs when there is high variability in infestation size and time required for treatment. Fox *et al.*'s (2009) spatially explicit simulation model offers an alternative for weed surveillance, with demographics and dispersal taken into account and a range of surveillance strategies that can be explored and evaluated.

When the programme objective is containment, surveillance resources should be targeted differently (usually at the invasion front or 'barrier zone'). One notable project has been the slowing of gypsy moth expansion in the US. Sharov *et al.* (1998) found that the most cost-effective solution was to place the highest density of traps ahead of the population front, at a distance determined by how far new colonies can arise from the established infestation.

Surveillance that is targeted for rapid control response is not well suited to observing changes in infestation density and/or extent, and will often lead to biased estimates (McMaugh 2005). In this case statistical sampling designs - such as random, variable probability or stratified sampling (see Section 3.2) – are preferable (see also Wikle and Royle 1999, McMaugh 2005, Samalens *et al.* 2007 and Royle *et al.* 2009). Occupancy modeling can be used to detect changes in extent with sampling effort modified for situations where detectability is imperfect (e.g. Field *et al.* 2005, Fitzpatrick *et al.* 2009).

Remote sensing can form part of monitoring surveillance when the pest (plant or animal) covers a large area of the landscape, and when it can be effectively distinguished within this landscape. Lawes and Wallace (2008) and Narumalani *et al.* (2009) provide examples of how remote sensing can be used for to gather information about changes in the spatial extent and density of invasive plants. Used in isolation, this method is unlikely to suit eradication or containment efforts where it becomes impossible to detect individuals at very low densities or where they are obscured by other vegetation.

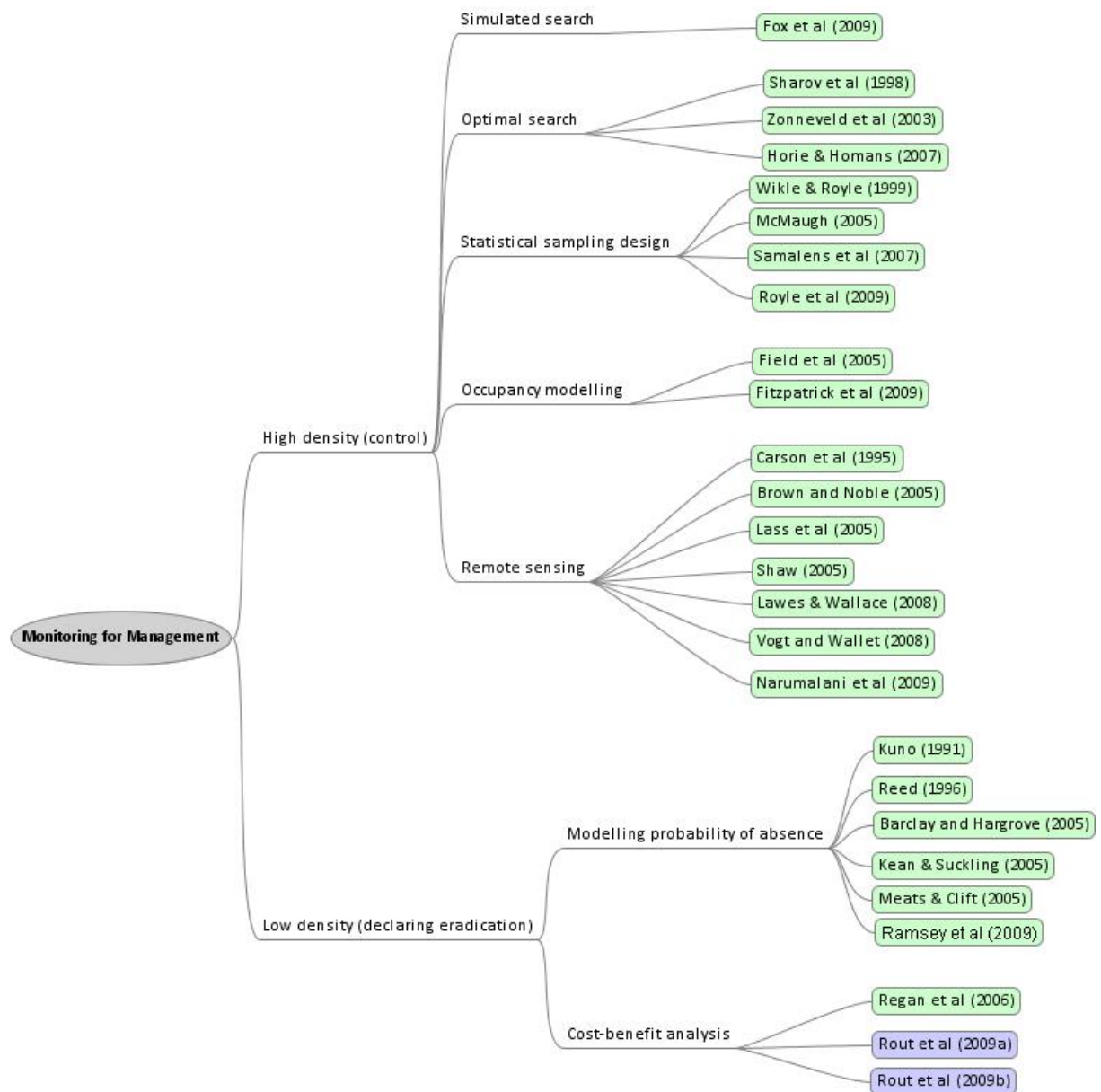


Figure 10. A mind map of surveillance techniques and tools for monitoring and assessment (Green denotes a method described in academic literature, pink denotes a readily-applicable surveillance tool and blue denotes ACERA research).

Prior to declaring eradication, pest populations will occur at low densities. Targeted surveillance plans, similar to those used for market access (Section 5.1) and early detection (Section 5.2) are most effective for finding those last individuals and evaluating eradication success. When sampling effort and detectability (see Section 3.3) can be quantified, usually the case where targeted (active) surveillance is used, the probability of successful eradication can be derived from simple probability models and survey data. A common feature of the probability models for monitoring eradication is that they require knowledge of both sampling effort and detectability (e.g. McArdle 1990, Kuno 1991, Reed 1996, Kéry 2002). For insect surveillance based on attractive traps, three research groups independently and simultaneously proposed probability-based frameworks to quantify the chance that a viable insect population may remain undetected after a given time, as a basis for declaring eradication. The approach of Barclay and Hargrove (2005) is conceptually the simplest. Meats and Clift (2005) also considered the effects of temperature on population increase. Kean and Suckling (2005) incorporated temperature effects in both population increase and trap efficacy, and the model was used to support the termination of a large eradication programme. The latter approach has since been generalized into a GIS-based system for mapping the probability of eradication across an eradication zone depending on the specific spatial and temporal deployment of traps (Kean 2008).

Research on the fossil record and rare species ecology have driven the development of methods to estimate extinction (eradication) times from presence-only sighting records (e.g. Solow 1993, 2005). A range of such methods was reviewed and evaluated by Rivandeira *et al.* (2009), who concluded that most perform well when sampling effort, though unknown, is relatively homogeneous through time. These authors also supplied an Excel spreadsheet for estimating extinction time from sighting records.

Recent studies have adopted Bayesian methods to quantify the success of vertebrate eradication programmes based on shooting or trapping methods (Solow *et al.* 2008, Ramsey *et al.* 2009). Another recent advance has been the incorporation of benefit-cost criteria into weed eradication monitoring models to trade the cost of ongoing monitoring without detection against the risk that the weed is still extant and will escape (Regan *et al.* 2006, Rout *et al.* 2009 a,b and ACERA 0604). Regan *et al.* (2006) found the following 'rule of thumb' using a static optimization:

$$n^* = \ln \{-C_s / (C_e \times \ln r)\} / \ln \quad (11)$$

where  $n^*$  is the optimal number of surveys without detection to conduct;  $C_s$  is the cost of each survey; and  $r$  is the probability that the invasive plant is not detected but is still present as either adults or seed. A dynamic optimization, using stochastic dynamic programming (SDP - an optimization algorithm for finding optimal strategies over time for systems with a finite number of 'states') accommodated the possibility of resighting the weed during these eradication surveys better. It was found that the rule of thumb offers a good approximation to the SDP solution except when there is a high probability of weed persistence (e.g. high seed longevity). In this case the rule of thumb tends to underestimate the number of surveys without detection to be conducted and the full dynamic optimization is a preferable approach.

Rout *et al.* (2009a) noted that the estimates of detectability and persistence required for Regan *et al.*'s (2006) model (which appear as parameter  $r$ ) are often difficult to estimate, and replaced them with Solow's (1993) method of estimating  $r$  using sighting records. In this case surveys are not required to be regularly spaced through time but do need to be independent of each other. Rout *et al.* (2009) obtained a rule of thumb analogous to Regan *et al.*'s (2006) equation X, however it must be solved numerically. They also derived an approximation to this rule:

$$d^* \approx s_n \{ (n-1)^2 \pi / [s_n (1-\pi) R] \}^{1/n} - s_n \quad (12)$$

This approximation gives results that are within one absent survey of the exact optimal (derived by SDP) for most parameter combinations, and tend to underestimate the optimal result when the sighting frequency is very low. The approximation also tends to slightly overestimate the optimal result (by up to three surveys) when the sighting frequency is moderately low. Figure 11 (see Figure 5 in Rout *et al.* 2009a) shows the estimated probability that bitterweed is extant in Queensland, as a function of consecutive absence surveys, using four of these methods.

Rout *et al.* (2009b) subsequently applied an info-gap uncertainty analysis to this problem of when to declare eradication. They set a threshold on the acceptable net expected costs of survey and weed escape and explored solutions that were robust to uncertainty in the probability of weed presence. The robust-optimal number of surveys is always larger than optimal number assuming that probability of weed presence is known. The lower the required net expected costs, the more surveys must be conducted to buffer against uncertainty.

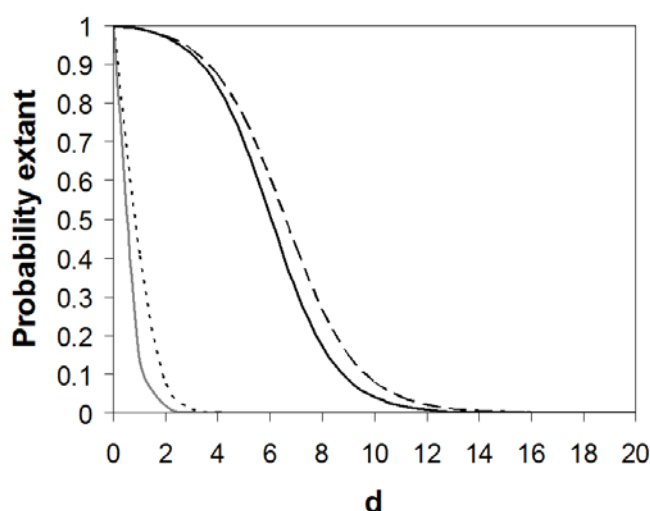


Figure 11. The probability that bitterweed is extant as a function of the number of consecutive absent surveys (shown up to  $d = 20$ ), calculated with four different methods. The solid grey line uses Regan *et al.*'s (2006) rule of thumb, and the dotted line uses Regan *et al.*'s (2006) SDP. Both of these used the best estimate parameters described in Regan *et al.* (2006), and assumed surveys are conducted annually. The solid black line is calculated using Solow's (1993) equation, and the dashed line is calculated using the declining sighting rate equation. Plot appears as Figure 5 in Rout *et al.* (2009a).

## Summary

Monitoring surveillance is used to assess the progress of existing containment or eradication programmes towards their respective objectives. Relevant tools that may be used for monitoring surveillance are listed in Table 7. How to efficiently allocate surveillance resources varies substantially depending on the purpose of the programme and the infestation density. Targeted surveillance is most efficient for controlling infestations, with targeting for containment focusing on the invasion front and targeting for eradication similar to surveys for early detection (see Section 5.2). Targeted surveillance, however, does not necessarily provide useful data for monitoring trends in density and extent. Long-term programmes should consider statistical sampling techniques to evaluate progress.

As eradication draws near, populations become sparse and difficult to detect. This phase has much in common with the objectives of market access (Section 5.1) and early detection (Section 5.2) and similar techniques can be used to assess that probability that the pest is still present. Furthermore, benefit-cost analyses have been developed to determine how long we should invest in surveillance without detection before safely declaring eradication.

These substantial differences between programme objectives and appropriate surveillance designs highlight the importance of periodically assessing and re-evaluating pest management. This will ensure that the pest management programme is guided by the right objective and supported by appropriate surveillance. In Section 6 we will discuss tools that can support this process of decision making.

**Table 7. Surveillance tools for monitoring.**

Technique	Use of technique	Application	Reference	Available tools
Survey design	Gather information on the extent and density of a pest or disease	8 case studies presented	McMaugh (2005)	formulae
Optimization, SDP	Determining cost effectiveness of further eradication monitoring when sample effort is known	Bitterweed in Queensland	Regan <i>et al.</i> (2006)	Rules of thumb
Optimization, SDP	Determining cost effectiveness of further eradication monitoring based on sighting records	Bitterweed in Queensland	Rout <i>et al.</i> (2009a)	Rules of thumb
Robust optimization, info-gap	Determining robustness of eradication monitoring	-	Rout <i>et al.</i> (2009b)	Rules of thumb
Statistical methods	Inferring extinction time from sighting records	General	Rivandeira <i>et al.</i> (2009)	Excel spreadsheet <a href="http://esapubs.org/archive/ecol/E090/084/suppl-1.htm">http://esapubs.org/archive/ecol/E090/084/suppl-1.htm</a>

## 6. Decision making

Justifiable and efficient surveillance is planned in the context of decision making. What kind of survey data will support future decision making and inform future actions? How will it be incorporated? The answer to these questions should guide survey design.

In this section, we discuss tools that aid decision making for pest incursion management but take a broader view than just survey design. Some provide guidance on whether it is most prudent to eradicate, contain or not control an incursion, while others address allocation of resources amongst different activities (such as control, surveillance and research). Some models explicitly include the contribution of surveillance to overall management, others focus on other management activities and rely only implicitly on survey data.

### 6.1 Short-term decision making

Short-term decision making may be required immediately following the first detection of a species (see Figure 3). In some cases, a protocol may have been agreed upon prior to detection (e.g. PHA 2006; 2007; AHA 2008a) and management of the infestation can proceed immediately. This is most likely to be the case when the species has been recognized as invasive elsewhere and of potential threat to agriculture.

In the absence of such a plan, a rough assessment of the threat posed by the species is needed. Questions to be answered might include:

- Is the species known to be invasive elsewhere?
- Are related species known to be invasive locally?
- What is the species' potential to establish in the local environment, for example, what is the local distribution of hosts or suitable habitat?
- What would the consequences of species establishment be?
- What methods of species control are available?

Such questions might be answered readily if the species has previously occurred in the area, but often there will be high uncertainty surrounding a threat assessment. It is potentially much more cost-effective, however, to eliminate an infestation at an early stage than to embark on an eradication programme later, when the magnitude of the threat has been assessed in more detail and the species may have spread and caused damage. For example, Harris and Timmins (2009) analyzed data from 58 New Zealand Department of Conservation weed control projects and estimated that if a new infestation of a known weed is found, it should on average be controlled immediately if control will cost less than



NZ\$47 000 (including follow-up surveillance). Furthermore, a newly found plant of unknown weediness should be controlled immediately if control will cost less than NZ\$7000 (although this figure is likely to be an underestimate).

## 6.2 Long-term decision making

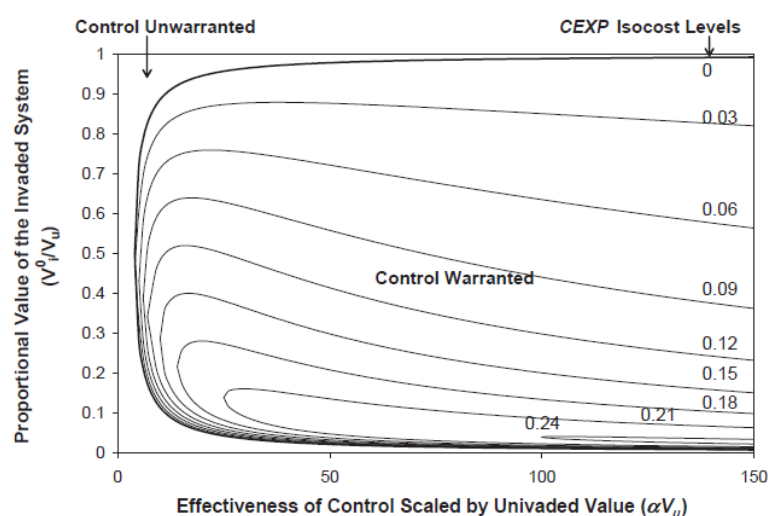
After the initial response, further decision making will be required periodically during incursion management. As the infestation is delimited, a more detailed threat assessment becomes possible and long-term management plans can be developed. Is the purpose of management to eradicate, contain or watch the species? What resources can or should be deployed for this purpose? Table 8 summarizes key tools that can help answer these questions.

A benefit-cost analysis (see Section 3.1) can identify what control activities are less costly than the pest damages they prevent. Many studies have used a cost-benefit approach and optimization methods to identify the intensity of control that will minimize total expected time-discounted costs of control and damage caused by the target species (e.g. Sharov and Liebhold 1998, Olson and Roy 2002, Buhle *et al.* 2005, Leung *et al.* 2005, Hastings *et al.* 2006, Yokomizo *et al.* 2009 ). They assume, however, that the density and/or distribution of the pest population is known with certainty. The optimal intensity of control that these studies derive may not explicitly relate to the objectives of eradication, containment and watching, and may even implicitly shift from one objective to another as the incursion and its management progress. Leung *et al.* (2005) developed the following rules of thumb for optimal control of an infestation:

- optimal expenditure ‘increases with the value of the system’ (under threat);
- optimal expenditure decreases as the unpreventable damages caused by pest presence increases;
- optimal expenditure ‘depends upon damages...but will not exceed 1/4 the original value of the system’ (under threat);
- the ratio of control expenditure to the initial value of the threatened system ‘forms a parabolic relationship with controllable damage and effectiveness of control’; and
- optimal control expenditure is zero if the ratio of control effectiveness to the initial value of the threatened system is less than four (from Table 1 in Leung *et al.* 2005).

Figure 12 (from Figure 2 in Leung *et al.* 2005) demonstrates how the optimal control expenditure can be found as a function of ratio of control effectiveness to the initial value of the threatened system and the ratio of control expenditure to the initial value of the

threatened system. To justify implementing control effort, the control method's effectiveness must be sufficiently high in relation to the value of the system being protected from damage. Large control effort is optimal when the value of the system after a pest incursion is substantially less than the value of the pest-free system. These rules-of-thumb have utility when the value of the uninvaded and invaded system (with and without control), and the cost of control that is required to reduce the damage caused by the invasion, can be measured or estimated. Measuring the value of a system can be difficult if attributes of the system are not directly traded in the market place. The methods that can be used to estimate these non-market values are discussed in Section 3.1.



**Figure 12.** The optimal control expenditure, as a proportion of the initial value of the system (Source: Leung *et al.* 2005, Figure 2).

Sharov and Liebhold (1998) and Cacho *et al.* (2008) have modelled the relationship between control and the management objective (eradicate, contain, no control) more explicitly. Each group modelled the spread of the invasive species from its original site of infestation. Assuming that damage is proportional to the area (but not density) of the infestation, it is optimal to target control at the perimeter of the infestation, or 'barrier zone'. Then the control intensity can be expressed in terms of the infestation's rate of spread - a negative rate indicates that eradication is optimal, a zero rate indicates containment, a positive rate below the maximum spread means that infestation should be delayed, while the maximum rate means that the infestation will spread uncontrolled.

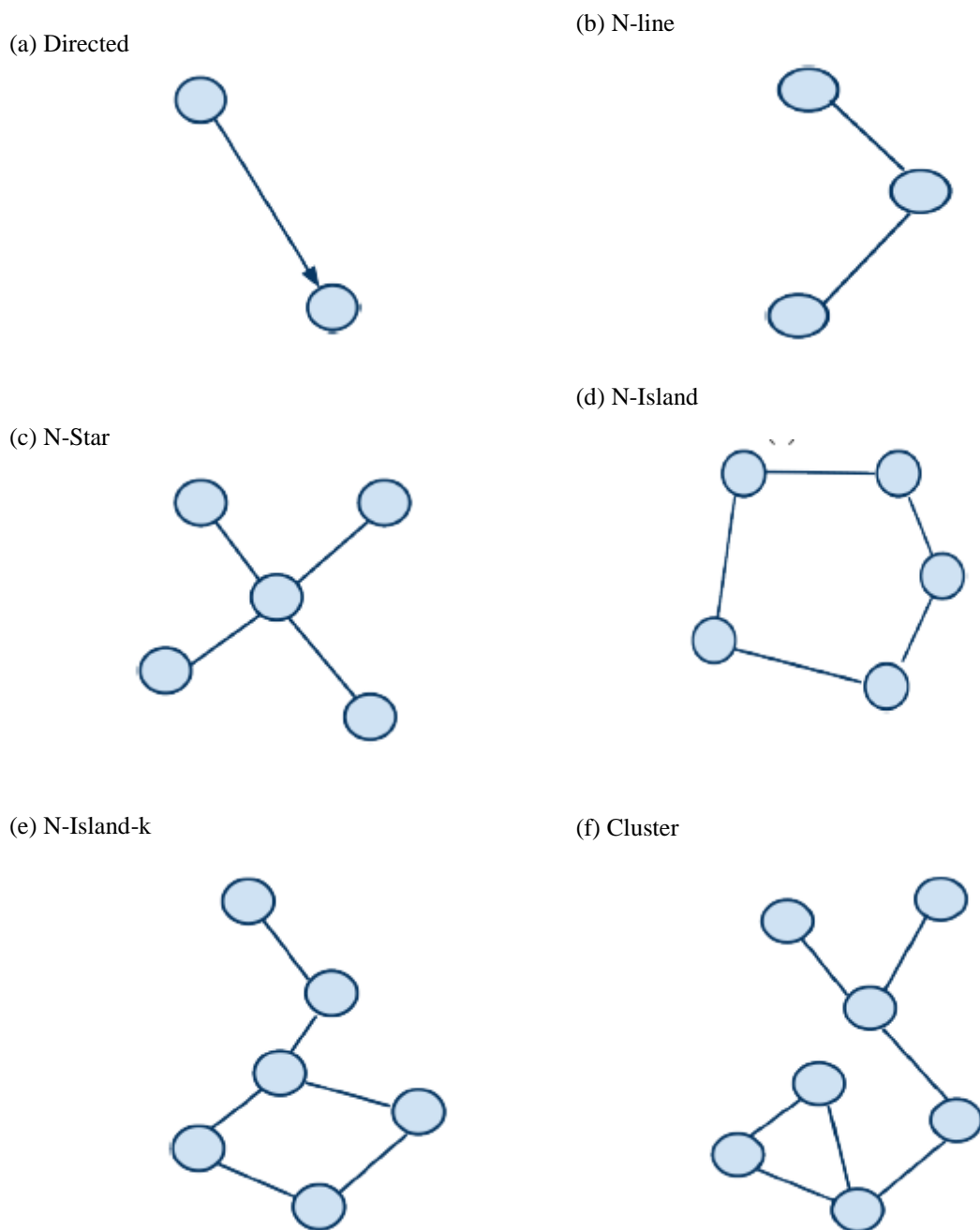
Other control-focused studies address how to target control resources amongst life history stages most effectively (Buhle *et al.* 2005, Hastings *et al.* 2006) or across space (Moody and Mack 1988, Taylor and Hastings 2004, Chades 2009). With the exception of Chades (ACERA 2009), these studies assume that the distribution of the pest is known, presumably

from surveillance data. Moody and Mack (1988) and Taylor and Hastings (2004) explore the utility of targeting outlier populations (comparable to Sharov and Liebhold's (1998) 'barrier zones', above) versus the core infestation. Chades (2009) builds spatially explicit networks of infestation to identify where control efforts should be targeted, based on their level of connectivity. She gave the following recommendations for networks with different structures, when pest distribution is known:

- source-sink or directed networks: manage the source first and the sink last (see Figure 13a);
- N-line networks: start from an extremity of the line and keep managing parcels following the same direction (see Figure 13b);
- N-Star networks: manage the infected satellite parcels until the number of satellite parcels empty is equal to or greater than the number of satellite parcels infected. Then manage the central parcel and the remaining infected satellite parcels (see Figure 13c);
- N-Island networks: start managing one parcel and then manage the closest parcels in any direction (see Figure 13d);
- N-Island-k networks: start managing the extreme parcel of the network, manage the k-line, manage the connecting node and manage successively the parcels that are the closest to the connecting node. If an island network is connected to several lines start managing from the longest line (see Figure 13e); and
- cluster network: start from the smaller cluster, if the clusters are identical start from any cluster, if a cluster is less connected start from the least connected cluster (see Figure 13f).

The principles found from these motifs are applicable to numerous variations on connectivity. Solutions for specific networks can be calculated using Chades' software, demonstrated on YouTube (see:

- 3-node network: [http://www.youtube.com/watch?v=wuOvbCu\\_nJc](http://www.youtube.com/watch?v=wuOvbCu_nJc);
- 9-node network: <http://www.youtube.com/watch?v=UMsKMd-X8QE>;
- 5-node directed network: <http://www.youtube.com/watch?v=muLzZ-3hIvM>).



**Figure 13. Example motif network configurations for Chades (2009).**

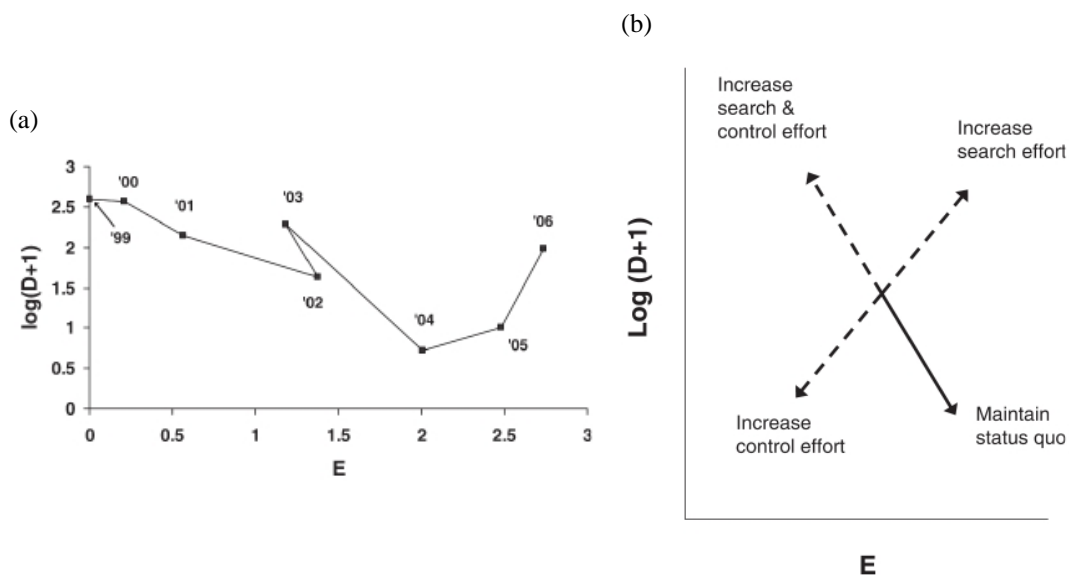
While these studies of optimal control assume that the distribution, abundance and/or density of the infestation are known precisely, surveillance inevitably gives only partial information. Simulation of infestation growth and management can be a more tractable way of exploring the performance of various search and control strategies. For example, Cacho and Pheloung (2007) have developed WeedSearch, freely available software that runs within Excel, to simulate weed demographics, detection and costs.

Panetta and Lawes (2007) propose weed delimitation and extirpation criteria that require fewer inputs and account for imperfect detectability. They defined a delimitation measure  $D_n$  in year  $n$  as

$$D_n = \frac{A_d}{[P_n + \log(A_s + 1)]} \quad (13)$$

where  $A_d$  is the area of infestation newly detected in year  $n$ ;  $P_n$  is the proportional change in total infested area between year  $n-1$  and year  $n$ ; and  $A_s$  is the area searched in year  $n$  (equation 7, Panetta and Lawes 2007). They define an extirpation measure  $E_n$  in year  $n$  as the mean of the frequency distribution of time since last detection for multiple infestations.

Panetta and Lawes (2007) recommend that the coordinates  $[E_n, \log(D_n + 1)]$  be plotted through time as an 'eradograph', to assess progress towards eradication. When a programme is successful,  $E_n$  will be larger than the seed longevity (non-detection time) of the species, while  $\log(D_n+1)$  will approach zero. Figure 14a reproduces their eradograph for branched broomrape, where the latter few years of data suggest a failure to effectively delimit the infestation. Eradograph trends that indicate eradication measures are not currently successful also indicate which components of management require more resources (see Figure 14b).



**Figure 14. (a) Eradograph for a branched broomrape eradication project (Source: Panetta and Lawes 2007, Figure 2), and (b) recommended resource deployment as a function of eradograph trend (Source: Panetta and Lawes 2007, Figure 4).**

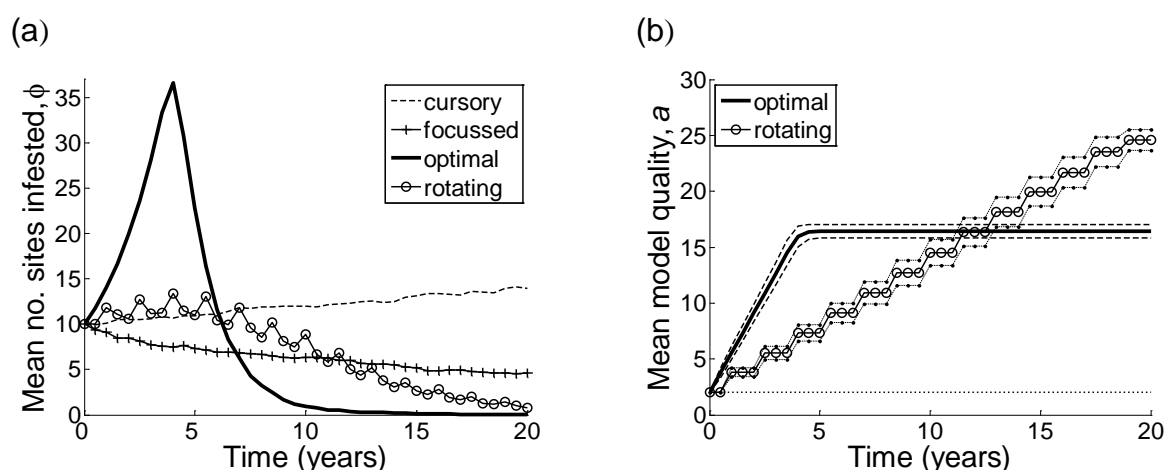
Two ACERA projects have explored the optimal deployment of resources across multiple incursion management activities with explicit consideration of surveillance. Chades (ACERA 0902) extended her network model of connected infestations to accommodate imperfect

survey information. Chades' software can solve problems involving up to six sites and is demonstrated on YouTube ([http://www.youtube.com/watch?v=Ro-jKitb\\_-w](http://www.youtube.com/watch?v=Ro-jKitb_-w)). To maximize the probability of eradication, optimal strategies generally apply control and survey effort repeatedly, especially to well-connected sites, even if the species is not observed.

Baxter and Possingham (ACERA 0604) investigated the optimal allocation of resources to broad-scale surveys (to assist delimitation), targeted surveys (to assist control) and research to improve species distribution models and hence the accuracy of future surveys. They adopted an objective of minimizing the area of infestation with a hundred-fold favourable outcome for total eradication. They found that:

- over the long-term there is a benefit to investing in research, at the expense of survey and control, in early time steps. Research may not be justified over shorter time frames; and
- when knowledge is poor, targeted surveys are of little use and broad scale searches are preferable. When knowledge and infestation are at intermediate levels, targeted surveys are optimal. When knowledge and infestation are high, even targeted strategies will provide broad coverage.

While several initial years of research may optimize control success over a long time frame, it may also yield rapid population spread during these initial years. Other heuristic strategies may provide more acceptable results (see Figure 15), though the long-term probability of eradication is likely to be substantially lower (97% versus 59%, in Baxter and Possingham's example).



**Figure 15. Simulated performance of invasive species management over 20 years by Baxter and Possingham (in review). (a) Comparison of four management strategies: cursory widespread searches; intensive focused searches; optimal state-dependent strategy recommended by SDP; and continual rotating between cursory search, model-improvement and focused search. (b) Acquisition of knowledge when the optimal and rotational strategies are implemented. The two non-learning strategies (cursory and focused searching remain at the initial level of  $a = 2$  (dotted line).**

For effective incursion management, surveillance must be understood and designed in the context of other management activities such as research and control. Tools that guide the allocation of resources between surveillance and other activities must acknowledge the quality of data obtained from surveillance (which will always be imperfect, for example, see Cacho and Pheloung 2007, Panetta and Lawes 2007, Chades ACERA 0902, Baxter and Possingham ACERA 0604). More common are studies that assume perfect and complete surveillance data (i.e. full knowledge of pest distribution and/or density), which recommend optimal levels of pest control see, for example, Sharov and Liebhold 1998, Olson and Roy 2002, Buhle *et al.* 2005, Leung *et al.* 2005, Hastings *et al.* 2006, Yokomizo *et al.* 2009 ). While they contribute important findings for cost-effective management, they may underestimate the cost and overestimate the feasibility of successful pest control if they are adopted without further consideration of the role surveillance plays.

**Table 8. Summary of deployable tools and techniques for long-term decision making.**

Technique	Use of technique	Application	Reference	Available tools
Optimization by calculus	Determine optimal expenditure on control to minimize the costs of control and damage	-	Leung <i>et al.</i> (2005)	Rules of thumb (see main text) and optimal control plot (Figure 8)
Optimization using factored MDP and algebraic decision diagrams	Prioritize infestation control among sites connected by dispersal	-	Chades (ACERA 0902)	Rules of thumb (see main text and Figure 9) and software
Simulation	Evaluate feasibility of weed eradication	-	Cacho and Pheloung (2007)	WeedSearch software for Excel 2003, available at <a href="http://www-personal.une.edu.au/~ocacho/weedsearch.htm">http://www-personal.une.edu.au/~ocacho/weedsearch.htm</a>
Eradograph	Evaluate progress towards weed eradication	Branched broomrape in South Australia	Panetta and Lawes (2007)	Equations and plotting (see main text and Figure 10)
Optimization using Perseus algorithm for spatial POMDPs	Prioritize infestation monitoring and control among sites connected by dispersal	-	Chades (ACERA 0902)	Rules of thumb (see main text) and software
Optimization by SDP	Allocate resources between broad scale searches, targeted searches and knowledge acquisition	Red imported fire ants ( <i>Solenopsis invicta</i> ) in south-east Qld	Baxter and Possingham (ACERA 0604)	Rules of thumb (see main text)

## 7. Discussion

The primary purpose of post-border surveillance is to provide evidence of absence of a pest or disease, or to determine the presence, prevalence and distribution of pests and diseases. The outcome of surveillance is a reduction in the risk of specific pests and diseases becoming established in a new location, particularly pests and diseases that have the potential to cause considerable harm to agricultural production, trade opportunities or valued ecosystems.

We have categorized and discussed post-border surveillance techniques according to whether the purpose is to maintain or establish market access, enable early detection, delimit the extent of an incursion, or enable effective monitoring. Because planning, implementation and evaluation of surveillance activities are also critical elements of post-border surveillance we have included a discussion on methods and tools for undertaking decision making in the surveillance context.

This report focuses mainly at the level of a biosecurity manager who is faced with a range of surveillance problems and is responsible for allocating a finite amount of resources to competing surveillance activities. That said, this report should also provide useful information and insights for policy-makers and others with an interest in biosecurity surveillance. Given our target audience, we have highlighted tools that are freely available for use in each aspect of post-border surveillance and that require limited technical expertise to apply. The tools described range from rules of thumb and formulae to user-friendly interfaces for simulation models. Notably, there are few tools available for delimitation, although one theoretical tool shows promise as something that could be progressed to the tool stage if time, resources and data permit.

The examples we use in our discussion of post-border surveillance activities focus on weeds and pests and diseases of plants and animals, with some of relevance to vertebrate and marine pest management. Obvious omissions are examples of surveillance tools that are used in forestry and tools used to detect infectious diseases that cause harm to human health (for a review of the latter see Vrbova *et al.* 2009).

We present the discussion of surveillance techniques from the point of view of single-species management. Often though, surveillance is undertaken for a range of species, simultaneously. There is scope, therefore, to investigate tools and techniques that may be used for multiple-species surveillance, similar to the work of Barrows *et al.* (2005) in monitoring multiple species for conservation.



The next stage of the current project is to develop scenarios, case studies and examples that illustrate the application of some of the tools discussed above, in circumstances relevant to their deployment in operational conditions in Australia. A key outcome from this next exercise should be improved post-border surveillance if, as hoped, these tools become more readily applied by biosecurity managers who may not have previously had the skills to apply them. Progress towards this objective is given in the following section.

## 7.1 Recommendations for case studies

Stage 3 of the project aims to develop scenarios, case studies and examples that illustrate the application of post-border surveillance tools in circumstances relevant to their deployment in operational conditions in Australia, with end-user involvement. Several meetings have been held with biosecurity managers across Australia to identify possible case studies.

On October 26 and 27 2009, participants from ACERA (Susie Hester, Andrew Robinson, Paul Pheloung, Mark Burgman) met with colleagues from the NT Department of Resources (NT DoR) (Andrew Tomkins, Sue Fitzpatrick, Helen Cribb, San Kham Hornby, Graham Schultz, Jim Swan). The objective of the meeting was to discuss the deployment of surveillance tools and the development of case studies to illustrate their use.

DoR personnel presented outlines of surveillance issues related to animal, plant and marine biosecurity, BioSIRT, emergency response, new initiatives, national and local collaborations and needs, and prospects for further development of surveillance activities. Discussion focused on areas where new and established technologies might assist DoR staff to better deploy limited resources. The potential case studies and tools identified by the DoR staff are listed in Table 9.

**Table 9. A sample of potential case studies and illustrations from the Northern Territory.**

Context / Issue	Tool	Examples
Pest/Disease freedom	Scenario tree	Citrus diseases (citrus canker, citrus greening) Bee pests (Small Hive Beetle, varroa mite) Fruit flies (Queensland fruit fly)
Eradication (stop-go)	Cost-benefit	Mango Malformation Disease (MMD), Grape vine diseases
Urban surveys for new pests	Survey design	Guava rust Giant African snail
Delimitation	Spatial models	MMD
Vessel inspections	Profiling	Inspection priorities
Barrier zones	Dynamic survey design	Surveillance for animal diseases
Surveillance trends	Trend analysis	Fruit fly surveillance data

Other potential case studies included: declaring absence of black-spined toad (a Malaysian species) (Kirsten Parris, Vic); understanding the impact of orange hawkweed, with a view to informing a proposal for a national response programme in the Snowy Mountains of NSW (Peter Espie, NZ and Snowy Mountains Committee, NSW/Vic); applying the scenario trees method to gypsy moth surveillance systems in New Zealand (John Kean, AgResearch, NZ); and determining the criteria for when to stop looking for European house borer (Mario D'Antuono, WA).

Following additional discussions with biosecurity managers at a state and national level, it was decided that the following case studies and scenarios would be developed into usable tools:

- a survey design tool for citrus canker in the Northern Territory; and
- an extirpation-monitoring tool for orange hawkweed in Victoria.

These case studies will be described in more detail in the milestone report of Stage 3 of the project.



## 8. References

- Animal Health Australia (2008a) Summary Document (Version 3.1) *Australian Veterinary Emergency Plan (AUSVETPLAN)*, Edition 3, Primary Industries Ministerial Council, Canberra, ACT.
- AHA (Animal Health Australia) (2008b). *National TSE Surveillance Program (NTSESP) National Guidelines for Field Operations: July 2009 to June 2010*, [http://www.animalhealthaustralia.com.au/shadomx/apps/fms/fmsdownload.cfm?file\\_uuid=36475B13-C131-9DA4-5FE5-869D09710210&siteName=aahc](http://www.animalhealthaustralia.com.au/shadomx/apps/fms/fmsdownload.cfm?file_uuid=36475B13-C131-9DA4-5FE5-869D09710210&siteName=aahc)
- Animal Health Australia (2005). Livestock Health [http://www.animalhealthaustralia.com.au/shadomx/apps/fms/fmsdownload.cfm?file\\_uuid=D8ECBC49-C72D-2948-A2E7-FCD25EE5805C&siteName=aahc](http://www.animalhealthaustralia.com.au/shadomx/apps/fms/fmsdownload.cfm?file_uuid=D8ECBC49-C72D-2948-A2E7-FCD25EE5805C&siteName=aahc)
- AusVet Animal Health Services (n.d.). Analysis of complex surveillance systems, <http://freedom.ausvet.com.au/pmwiki/pmwiki.php?n=Freedom.FreedomTrail>
- Bailey LL, Hines JE, Nichols JD and MacKenzie DI (2007) Sampling design trade-offs in occupancy studies with imperfect detection: examples and software. *Ecological Applications* **17**, 281–290.
- Barclay HJ and Hargrove JW (2005) Probability models to facilitate a declaration of pest-free status, with special reference to tsetse (Diptera: Glossinidae). *Bulletin of Entomological Research* **95**, 1–11.
- Barrett S, Whittle P, Mengersen K and Stoklosa R (2009) Biosecurity threats: the design of surveillance systems, based on power and risk. *Environmental and Ecological Statistics* 10.1007/s10651-009-0113-4.
- Barrows CW, Swartz MB, Hodges WL, Allen MF, Rotenberry JT, Li B-L, Scott TA and Chen X (2005) *Journal of Wildlife Management* **69**(4), 1333–1345.
- Baxter P and Possingham HP (2009) Allocating resources between knowledge acquisition and surveillance, in *Optimal allocation of resources to emergency response actions for invasive species*. Final Report, ACERA 0604, University of Melbourne p12-13.
- Baxter P and Possingham HP (submitted 2009). Optimising search and removal of invasive pests: the value of knowledge acquisition. submitted to *Ecology Letters*
- Beale R, Fairbrother J, Inglis A and Trebeck D (2008) *One biosecurity: a working partnership, the independent review of Australia's quarantine and biosecurity arrangements report to the Australian government*, Commonwealth of Australia.
- Biosecurity Australia (2007) *Revised Draft Import Risk Analysis Report for the Importation of Cavendish Bananas from the Philippines, Part A*. Biosecurity Australia, Canberra.
- Boland P (2005). *A Review of the National Sentinel Hive Program in Queensland, New South Wales, Victoria, Western Australia and the Northern Territory*, Biosecurity Australia.
- Brown JA, Harris S and Timmins S (2004). Estimating the maximum interval between repeat surveys. *Austral Ecology* **29** 631–636.
- Brown RB and Noble SD (2005) Site-specific weed management: sensing requirements – what do we need to see? *Weed Science* **53**: 252-258.
- Buckland ST, Anderson DR, Burnham KP, Laake JL, Borchers DL and Thomas L (2001) *Introduction to Distance Sampling: Estimating Abundance of Biological Populations*. Oxford University Press, Oxford, UK.
- Buhle ER, Margolis M and Ruesink JL (2005) Bang for buck: cost-effective control of invasive species with different life histories. *Ecological Economics* **52**, 355–366.
- Bulman LS, Kimberley MO, Gadgil PD (1999) Estimation of the efficiency of pest detection surveys. *New Zealand Journal of Forestry Science* **29**, 102–115.
- Byers JA, Anderbrant O and Löfqvist J (1989) Effective attraction radius: a method for comparing species attractants and determining densities of flying insects. *Journal of Chemical Ecology* **15**, 749–765.
- Cacho OJ, Hester S, Spring D and Mac Nally R (2010) Allocating surveillance effort in the management of invasive species: a spatially-explicit model. *Environmental Modelling and Software*. 25: 444-454.
- Cacho OJ and Hester S (in press). Deriving efficient frontiers for effort allocation in the management of invasive species. *Australian Journal of Agricultural and Resource Economics*.
- Cacho OJ, Spring, D, Pheloung, P and Hester S (2006) Evaluating the feasibility of eradicating an invasion. *Biological Invasions* **8**, 903–917.
- Cacho OJ, Hester S and Spring D (2007) Applying search theory to determine the feasibility of eradicating an invasive population in natural environments. *Australian Journal of Agricultural and Resource Economics* **51**, 425–443.

- Cacho OJ and Pheloung P (2007) Weed Search. <<http://www-personal.une.edu.au/~ocacho/weedsearch.htm>>.
- Cacho OJ, Wise R, Hester S and Sinden J (2008) Bioeconomic modeling for control of weeds in natural environments. *Ecological Economics* **65**, 559–568.
- Cacho OJ, Spring D, Hester S and Mac Nally R (2010) Allocating surveillance effort in the management of invasive species: A spatially-explicit model. *Environmental modelling and software* **25**(4), 444–454
- Cameron AR (1999) Survey Toolbox for livestock diseases – A practical manual and software package for active surveillance in developing countries. ACIAR Monograph 54.
- Cameron AR and Baldock FC (1998a) A new probability formula for surveys to substantiate freedom from disease. *Preventative Veterinary Medicine* **34**(1), 1–17
- Cameron, AR and Baldock, FC (1998b) Two-stage sampling in surveys to substantiate freedom from disease. *Preventative Veterinary Medicine* **34**(1), 19–30
- Cannon RM (2001) Sense and sensitivity—designing surveys based on an imperfect test. *Preventative Veterinary Medicine* **49**, 141–163.
- Cannon RM and Roe RT (1982) *Livestock Disease Surveys: A Field Manual for Veterinarians*, Australian Bureau of Animal Health, Canberra.
- Carson HW, Lass LW and Callihan RH (1995) Detection of yellow hawkweed (*Hieracium pratense*) with high resolution multispectral digital imagery. *Weed Technology* **9**, 477–483.
- CBIT (Centre for Biological Information Technology) (n.d.) Lucid Player 2. <<http://lucidcentral.cbit.uq.edu.au/lucid2/player/lucidplayer.htm>>.
- Chades I (2009) *Strategies for managing invasive species in space: deciding whether to eradicate, contain or control*. Draft final Report, ACERA Project 0902, University of Melbourne.
- Chee YE (2004) An ecological perspective on the valuation of ecosystem services. *Biological Conservation*, 120: 549 – 565.
- Chen G, Kéry M, Zhang J, Ma K (2009) Factors affecting detection probability in plant distribution studies. *Journal of Ecology* **97**, 1383–1389.
- Christian R and members of the community of practice for structured decision making (2009) *Community of practice for structured decision-making*. Final Report, ACERA Project 0809a, University of Melbourne.
- Christy MT, Adams AAY, Rodda GH, Savidge JA, Tyrrell CL (2010) Modelling detection probabilities to evaluate management and control tools for an invasive species. *Journal of Applied Ecology* **47**, 106–113.
- Cochran WG (1977) *Sampling Techniques*, 3<sup>rd</sup> Edition. Wiley.
- Cook D and Proctor W (2007) Assessing the threat of exotic plant pests. *Ecological Economics* **63**, 594–604.
- Czaja R and Blair J (2005) *Designing Surveys: a guide to decisions and procedures*, 2<sup>nd</sup> Edition, Pine Forge Press
- DAFF (Department of Agriculture, Fisheries and forestry) (2004) Report for the importation of bananas from the Philippines. Revised draft import risk analysis. Biosecurity Policy Memorandum 2004/19, 16 June.
- Decision Systems Laboratories (n.d.) About GeNIe and SMILE, <http://genie.sis.pitt.edu/>.
- DPI (Department of Primary Industries) (2008) Weed Spotter strategic recruitment plan. The State of Victoria Department Primary Industries.
- DPI (2009a) Draft invasive plants and animals, policy framework. State of Victoria Department of Primary Industries 30p. <<http://land.vic.gov.au/DPI/nrenfa.nsf/childdocs/-B3758D271BFF6C71CA256E760010DC14-109717C2FF913366CA2576080026662A?open>>.
- DPI (2009b) Draft weeds and invertebrate pests: Module 1 within the Invasive Plants and Animals Policy Framework. [http://land.vic.gov.au/DPI/nrenfa.nsf/LinkView/69DC0E4C5535980CCA257608002599572B72296A5108C4FFCA25734F0009F96F/\\$file/IPA\\_strategy\\_Module1\\_draft\\_for\\_consultationAug09.pdf](http://land.vic.gov.au/DPI/nrenfa.nsf/LinkView/69DC0E4C5535980CCA257608002599572B72296A5108C4FFCA25734F0009F96F/$file/IPA_strategy_Module1_draft_for_consultationAug09.pdf).
- Elith J and Leathwick JR (2009) Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology Evolution and Systematics*. **40**, 677–697.
- Elkinton JS, Cardé RT (1980) Distribution, dispersal, and apparent survival of male gypsy moths as determined by capture in pheromone-baited traps. *Environmental Entomology* **9**, 729–737.
- FAO (1996) Requirements for the establishment of pest free areas. *International Standards for Phytosanitary Measures Publication No. 4*. [https://www.ippc.int/file\\_uploaded/1146657783053\\_ISPM4.pdf](https://www.ippc.int/file_uploaded/1146657783053_ISPM4.pdf)

FAO (1997) Guidelines for surveillance. *International Standards for Phytosanitary Measures Publication No. 6*. <[https://www.ippc.int/file\\_uploaded/1146657977529\\_ISPM6.pdf](https://www.ippc.int/file_uploaded/1146657977529_ISPM6.pdf)>.

FAO (1998) International standards for phytosanitary measures: guidelines for pest eradication programmes. Report to Secretariat of the International Plant Protection Convention, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (1998) Determination of pest status in an area. *International Standards for Phytosanitary Measures Publication No. 8*. <[https://www.ippc.int/file\\_uploaded/1146658133679\\_ISPM8.pdf](https://www.ippc.int/file_uploaded/1146658133679_ISPM8.pdf)>.

FAO (1999) Requirements for the establishment of pest free places of production and pest free production sites. *International Standards for Phytosanitary Measures Publication No. 10*. <[https://www.ippc.int/file\\_uploaded/1146658291869\\_ISPM10.pdf](https://www.ippc.int/file_uploaded/1146658291869_ISPM10.pdf)>.

FAO (2006) *International Standards for Phytosanitary Measures 1 to 27* (2006 edition) Food and Agriculture Organisation of the United Nations, Rome.

FAO (2008a) Establishment of areas of low pest prevalence for fruit flies (*tephritidae*). *International Standards for Phytosanitary Measures Publication No. 30*. <[http://www.acfs.go.th/sps/downloads/ISPM\\_30.pdf](http://www.acfs.go.th/sps/downloads/ISPM_30.pdf)>

FAO (2008b) Methodologies for sampling of consignments. *International Standards for Phytosanitary Measures Publication No. 30*. <[http://www.acfs.go.th/sps/downloads/ISPM\\_31.pdf](http://www.acfs.go.th/sps/downloads/ISPM_31.pdf)>

Field SA, Tyre AJ and Possingham HP (2005) Optimizing allocation of monitoring effort under economic and observational constraints. *Journal of Wildlife Management* **69**(2): 473–482.

Fischer GW (1995) Range sensitivity of attribute weights in multiattribute value models. *Organizational Behavior and Human Decision Processes* **62**, 252–266.

Fitzpatrick MC, Preisser EL, Ellison AM, Elkinton JS (2009) Observer bias and the detection of low-density populations. *Ecological Applications* **19**, 1673–1679.

Fleischer SJ, Gaylor MJ, Edelson JV (1985) Estimating absolute density from relative sampling of *Lygus lineolaris* (Heteroptera: Miridae) and selected predators in early to mid-season cotton. *Environmental Entomology* **14**, 709–717.

Fox JC, Buckley YM, Panetta FD, Bourgoin J and Pullar D (2009) Surveillance protocols for management of invasive plants: modelling Chilean needle grass (*Nassella neesiana*) in Australia. *Diversity and Distributions* **15**, 577–589.

Froud KJ, Oliver TM, Bingham PC, Flynn AR and Rowsell NJ (2008) Passive surveillance of new exotic pests and diseases in New Zealand. In KJ Froud, AI Popay and SM Zydenbos (eds.) *Surveillance for biosecurity: Pre-border to pest management*. pp 97–110. New Zealand Plant Protection Society Inc., Hastings, New Zealand.

Garrard GE, Bekessy SA, McCarthy MA and Wintle BA (2008) When have we looked hard enough? A novel method for setting survey effort protocols for flora surveys. *Austral Ecology* **33**, 986–998.

Garrard, G, Bekessy S and Wintle B (2009) *Determining necessary survey effort to detect invasive weeds in native vegetation communities*. Final Report, ACERA Project 0906, University of Melbourne.

Gregoire, T.G. (1998) Design-based and model-based inference in survey sampling: appreciating the difference. *Canadian Journal of Forest Research* **28**(10): 1429–1447.

Hajkowicz SA, McDonald GT and Smith PN (2000) An evaluation of multiple objective decision support weighting techniques in natural resource management. *Journal of Environmental Planning and Management* **43**, 505–518.

Hammond JS, Keeney RL and Raiffa H (1998) Even swaps: a rational method for making trade-offs. *Harvard Business Review*, **76**(2):137–8, 143–8, 150.

Harris S, Brown J and Timmons S (2001) Weed surveillance – how often to search? *Science for Conservation* **175**.

Harris S and Timmins SM (2009) Estimating the benefit of early control of all newly naturalised plants. *Science for Conservation*. **292**.

Harrison M (2010) Harrison, M. 2010, *Valuing the Future: the social discount rate in cost-benefit analysis*, Visiting Researcher Paper, Productivity Commission, Canberra.

Hastings A, Cuddington K, Davies KF, Dugaw CJ, Elmendorf S, Freestone A, Harrison S, Holland M, Lambrinos J, Malvadkar U, Melbourne BA, Moore K, Taylor CM and Thomson D (2005) The spatial spread of invasions: new developments in theory and evidence. *Ecology Letters* **8**, 91–101.

Hastings A, Hall RJ and Taylor CM (2006) A simple approach to optimal control of invasive species. *Theoretical Population Biology* **70**, 431–435.

Hauser CE (2009) Where and how much? A spreadsheet that allocates surveillance effort for a weed. *Plant Protection Quarterly* **24**(3), 94–97

- Hauser CE and McCarthy MA (2009) Planning early surveillance for an invasive species, in *Optimal allocation of resources to emergency response actions for invasive species*. Final Report, ACERA 0604, University of Melbourne.
- Hauser CE and McCarthy MA (2009) Streamlining 'search and destroy': cost-effective surveillance for invasive species management, *Ecology Letters* **12**, 683–692.
- Hellström JS (2008) Opening address: Biosecurity surveillance. In *Surveillance for Biosecurity: Pre-border to pest management*. (Eds KJ Froud, Popay, AI and SM Zydenbos) pp. 1-9. New Zealand Plant Protection Society Incorporated.
- Hester S and Cacho OJ (in press). Optimisation of search strategies in managing biological invasions: a simulation approach. *Human and Ecological Risk Assessment*.
- Hester SM, Brooks SJ, Cacho OJ and Panetta FD (2010) Applying a simulation model to the management of an infestation of *Miconia* (*Miconia calvescens*) in the wet tropics of Australia. *Weed Research* **50**(3): 269-279.
- Hood, G.M., Barry, S.C. and Martin, P.A.J. (2009). Alternative methods for computing the sensitivity of complex surveillance systems. *Risk Analysis* **29**(2), 1686-1698.
- Hood G (2009) *PopTools version 3.1.0*. <http://www.cse.csiro.au/poptools/index.htm>
- Horie T and Homans F (2007) Optimal detection strategies for an established invasive forest pest. *American Agricultural Economics Association Annual Meeting*.
- IPPC (International Plant Protection Convention) (n.d.) *About the International Plant Protection Convention*, <https://www.ippc.int/>
- Jarrad F, Barrett S, Murray J, Parkes J, Stoklosa R, Mengersen K and Whittle P (2010) Improved design method for biosecurity surveillance and early detection of nonindigenous rats. *New Zealand Journal of Ecology*.
- Jennings C (2004) A brief history of the red imported fire ant eradication program. *The Australian Journal of Emergency Management*. **19** (3) 97–100.
- Joseph LN, Elkin C, Martin TG and Possingham HP (2009a) Modeling abundance using N-mixture models: the importance of considering ecological mechanisms. *Ecological Applications* **19**, 631-642.
- Joseph LN, Maloney RF and Possingham HP (2009b) Optimal allocation of resources among threatened species: a project prioritization protocol. *Conservation Biology* **23**(2): 328-338.
- Kean JM (2008) Spatio-temporal population probability models for monitoring eradication. International Congress of Entomology, 6-12 July 2008, Durban, South Africa.
- Kean JM and Suckling DM (2005) Estimating the probability of eradication of painted apple moth from Auckland. *New Zealand Plant Protection* **58**, 7–11.
- Kean JM, Phillips CB and McNeill MR (2008). Surveillance for early detection: lottery or investment? In KJ Froud, AI Popay and SM Zydenbos (eds.) *Surveillance for biosecurity: Pre-border to pest management*. pp. 11-17. New Zealand Plant Protection Society Inc., Hastings, New Zealand.
- Keeney RL (2002) Common mistakes in making value trade-offs. *Operations Research* **50**, 935–945.
- Keeney RL and Raiffa H (1993) *Decisions with multiple objectives*. Cambridge University Press, Cambridge, UK.
- Kéry M (2002) Inferring the absence of a species: a case study of snakes. *Journal of Wildlife Management* **66**: 330-338.
- Kompas T and Che N (2003) A Practical Optimal Measure: Papaya Fruit Fly in Australia. Draft Report to National Office of Animal and Plant Health Australia (unpublished).
- Kompas T, Che N, and Ha PV (2006) *An optimal surveillance measure against foot-and-mouth disease in the United States*. Working Paper 06-11, Crawford School of Economics and Government, Australian National University.
- Krebs C (1998) *Ecological Methodology* (2nd Edition) Benjamin Cummings.
- Krebs CJ and Boonstra R (1984) Trappability estimates for mark-recapture data. *Canadian Journal of Zoology* **62**, 2440–2444.
- Kuno E (1991) Verifying zero-infection in pest control: A simple sequential test based on the succession of sero-samples. *Researches on Population Ecology* **33**, 29–32.
- Lass LW, Prather TS, Glenn NF, Weber KT, Mundt JT and Pettingill J (2005) A review of remote sensing of invasive weeds and example of the early detection of spotted knapweed (*Centaurea maculosa*) and babysbreath (*Gypsophila paniculata*) with a hyperspectral sensor. *Weed Science* **53**, 242-251.



- Lawes RA and Wallace JF (2008) Monitoring an invasive perennial at the landscape scale with remote sensing. *Ecological Management and Restoration* **9**, 53–59.
- Leung B, Finnoff D, Shogren J and Lodge D (2005) Managing invasive species: Rules of thumb for rapid assessment. *Ecological Economics* **55**, 24–36.
- Leung B, Cacho O and Spring D (2010) Searching for non-indigenous species: rapidly delimiting the invasion boundary. *Diversity and Distributions*. DOI: 10.1111/j.1472-4642.2010.00653.x
- Lockhart CY (2008). *Surveillance for Diseases of Poultry with Specific Reference to Avian Influenza*. Massey University, Palmerston North, New Zealand.
- Luce MF, Payne JW and Bettman JR (1999) Emotional trade-off difficulty and choice. *Journal of Marketing Research*, 36, 143–159.
- MacKenzie DI and Royle JA (2005) Designing occupancy studies: general advice and allocating survey effort. *Journal of Applied Ecology* **42**, 1105–1114.
- MacKenzie DI, Nichols JD, Sutton N, Kawanishi K, Bailey LL (2005) Improving inferences in population studies of rare species that are detected imperfectly. *Ecology* **86**, 1101–1113.
- MacKenzie DI, Nichols JD, Lachman GB, Droege S, Royle JA and Langtimm CA (2002) Estimating site occupancy rates when detection probabilities are less than one. *Ecology* **83**: 2248–2255.
- MAFBNZ (Ministry of Agriculture and Forestry Biosecurity New Zealand) (2008) Biosecurity Surveillance Strategy: Review of the Current State of the Biosecurity Surveillance System <<http://www.biosecurity.govt.nz/files/pests/surv-mgmt/surv/mafbnz-surv-strategy-current-state.pdf>>.
- MAFBNZ (2009) Review of selected cattle identification and tracing systems worldwide: lessons for the New Zealand National Animal Identification and Tracing (NAIT) project. MAF Biosecurity New Zealand Information Paper No: 2009/03, Prepared by MAF Biosecurity New Zealand < <http://www.maf.govt.nz/mafnet/review-cattleident-systems-worldwide.pdf>>.
- McArdle BH (1990) When are rare species not there? *Oikos* **57**, 276–277.
- McCarthy MA, Thompson CJ, Hauser CE, Burgman MA, Possingham HP, Moir ML, Tiensen T and Gilbert M (in review) Resource allocation for efficient environmental management. *Ecology Letters*.
- McCallum DA (2005) A conceptual guide to detection probability for point counts and other count-based survey methods. In: ed. USDA Forest Service General Technical Report. Pp. 754–761.
- McMaugh T (2005) Guidelines for surveillance for plant pests in Asia and the Pacific. ACIAR Monograph No. 119.
- Martin PAJ, Cameron AR and Greiner M (2007a) Demonstrating freedom from disease using multiple complex data sources 1: A new methodology based on scenario trees. *Preventative Veterinary Medicine* **79**, 71–97.
- Martin PAJ, Cameron AR, Barford K, Sergeant ESG and Greiner M (2007b) Demonstrating freedom from disease using multiple complex data sources 2: Case study - classical swine fever in Denmark. *Preventative Veterinary Medicine* **79**, 98–115.
- Meats AW and Cliff AD (2005) Zero catch criteria for declaring eradication of tephritid fruit flies: the probabilities. *Australian Journal of Experimental Agriculture* **45**, 1335–1340.
- Meats A (1998) Cartesian methods of locating spot infestations of the papaya fruit fly *Bactrocera papayae* Drew and Hancock within the trapping grid at Mareeba, Queensland, Australia. *General and Applied Entomology* **28**, 57–60.
- Mehta SV, Haight RG, Homans FR, Polasky S and Venette RC (2007) Optimal detection and control strategies for invasive species management. *Ecological Economics* **61**, 237–245.
- MLA (Meat and Livestock Australia) (n.d.) National Livestock Identification System <http://www.mla.com.au/TopicHierarchy/IndustryPrograms/NationalLivestockIdentificationSystem/default.htm>.
- Moody ME and Mack RN (1988) Controlling the spread of plant invasions: the importance of nascent foci. *Journal of Applied Ecology* **25**, 1009–1021.
- Moore JL, Hauser CE, Bear J, Williams NSG and McCarthy MA (In review) Estimating detection-effort curves for plants using search trials.
- Moran A, Chisolm A and Porter M (Eds) (1991) *Markets, Resources and the Environment*. Allen and Unwin, Sydney.
- Murphy BD, Baird DB (2004) The feasibility of biosecurity surveillance of transitional facilities. Report to MAF Biosecurity New Zealand..
- Narumalani S, Mishra DR, Wilson R, Reece R and Kohler A (2009) Detecting and mapping four invasive species along the floodplain of North Platte River, Nebraska. *Weed Technology* **23**, 99–107.



- Nichols JD, Hines JE, Sauer JR, Fallon FW, Fallon JE, Heglund PJ (2000) A double-observer approach for estimating detection probability and abundance from point counts. *The Auk* **117**, 393–408.
- Norsys Software Corporation (n.d.) Netica™ Application, <http://www.norsys.com/netica.html>.
- OIE (World Organisation for Animal Health) (2009). *Terrestrial animal health code - 2009*. [http://www.oie.int/eng/normes/Mcode/en\\_sommaire.htm](http://www.oie.int/eng/normes/Mcode/en_sommaire.htm).
- Olson LJ and Roy S (2002) The economics of controlling a stochastic biological invasion. *American Journal of Agricultural Economics* **85**(5), 1311–1316.
- Paini DR, Worner SP, Cook DC, De Barro PJ and Thomas MB (2010) Using a self-organizing map to predict invasive species: sensitivity to data errors and a comparison with expert opinion. *Journal of Applied Ecology* doi: 10.1111/j.1365-2664.2010.01782.x
- Palisade Corporation (2010) Guide to using @RISK: Risk analysis and simulation add-in for Microsoft Excel. Version 5.5, February 2010 [http://www.palisade.com/downloads/manuals/EN/RISK5\\_EN.pdf](http://www.palisade.com/downloads/manuals/EN/RISK5_EN.pdf)
- Panetta F (2009). Weed eradication – An economic perspective. *Invasive Plant Science and Management* **2**, 360–368.
- Panetta FD and Lawes R (2005). Evaluation of weed eradication programs: the delimitation of extent. *Diversity and Distributions* **11**, 435–442.
- Panetta FD and Lawes R (2007) Evaluation of the Australian branched broomrape (*Orobanche ramosa*) eradication program. *Weed Science* **55**, 644–651.
- Perry G and Vice D (2009) Forecasting the risk of brown tree snake dispersal from Guam: a mixed transport-establishment model. *Conservation Biology* **23**(4), 992–1000.
- Peterson JT and Bayley PB (2004) A Bayesian approach to estimating presence when a species is undetected. (In WL Thompson ed. *Sampling Rare or Elusive Species*) – 173–188. Island Press, London, UK .
- PHA (Plant Health Australia) (2006) *National mango industry biosecurity plan*. Deakin, ACT <http://www.planthealthaustralia.com.au/>.
- PHA (2007) *National cherry industry biosecurity plan*. Deakin, ACT <<http://www.planthealthaustralia.com.au/>>
- Philippi T (2005) Adaptive cluster sampling for estimation of abundances within local populations of low-abundance plants. *Ecology* **86**(5), 1091–1100
- Prattley DJ, Morris RS, Stevenson MAR and Thornton R (2007) Application of portfolio theory to risk-based allocation of surveillance resources in animal populations. *Preventive Veterinary Medicine* **81**, 56–69.
- QDPIF (Queensland Department of Primary Industries and Fisheries) (2008) *National fire ant eradication program progress report 2007–2008*. Oxley, Qld.
- QNRM (Queensland Department of Natural Resources and Mines) (2006). *Siam Weed National Delimiting Survey Report*. Queensland Government.
- Queensland Government (n.d.) *Weedspotters Queensland network*. [http://www.derm.qld.gov.au/wildlife-ecosystems/plants/queensland\\_herbarium/weed\\_spotters\\_queensland\\_network.html](http://www.derm.qld.gov.au/wildlife-ecosystems/plants/queensland_herbarium/weed_spotters_queensland_network.html)
- Randall A (1981) *Resource Economics: An economic approach to natural resource and environmental policy*, Grid Publishing, Ohio.
- Ramsey DSL, Parkes J, Morrison SA (2009) Quantifying eradication success: the removal of feral pigs from Santa Cruz Island, California. *Conservation Biology* **23**, 449–459.
- Reed JM (1996) Using statistical probability to increase confidence of inferring species extinction. *Conservation Biology* **10**, 1283–1285.
- Regan TJ, McCarthy MA, Baxter PWJ, Dane Panetta F and Possingham HP (2006) Optimal eradication: when to stop looking for an invasive plant. *Ecology Letters* **9**, 759–766.
- Regan, H.M., Colyvan, M., and Burgman, M.A. 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological Applications* **12**(2) 618–628.
- Rew L, Maxwell B, Dougher F and Aspinall R (2006) Searching for a needle in a haystack: evaluating survey methods for non-indigenous plant species. *I* **8**, 523–539.
- Rivadeneira MM, Hunt G, Roy K (2009) The use of sighting records to infer species extinctions: an evaluation of different methods. *Ecology* **90**, 1291–1300.
- Rota CT, Fletcher RJ, Dorazio RM and Betts MG (2009) Occupancy estimation and the closure assumption. *Journal of Applied Ecology* **46**, 1173–1181.

- Rout TM and McCarthy MA (2009) Monitoring to declare eradication, in *Optimal allocation of resources to emergency response actions for invasive species*. Final Report, ACERA 0604, University of Melbourne.
- Rout TM, Salomon Y, McCarthy MA (2009a) Using sighting records to declare eradication of an invasive species. *Journal of Applied Ecology* **46**, 110–117.
- Rout TM, Thompson CJ and McCarthy MA (2009b) Robust decisions for declaring eradication of invasive species. *Journal of Applied Ecology* **46**, 782–786.
- Royle JA, Nichols JD, Karanth KU and Gopalaswamy AM (2009) A hierarchical model for estimating density in camera-trap studies. *Journal of Applied Ecology* **46**, 18–127.
- Saaty TL (1980). *The analytic hierarchy process. Planning, setting priorities, resource allocation*. McGraw Hill, New York.
- Samalens JC, Rossi JP, Guyon D, Van Halder I, Menassieu P, Piou D and Jactel H (2007) Adaptive roadside sampling for bark beetle damage assessment. *Forest Ecology and Management* **253**, 177–187.
- Schreuder HT, Gregoire TG and Wood GB (1993) *Sampling methods for multiresource forest inventory*. Wiley, New York.
- Schmidt D, Spring D, Mac Nally R, Thomson JR, Brook BW, Cacho O and McKenzie M (2010) Finding needles (or ants) in haystacks: predicting locations of invasive organisms to inform eradication and containment. *Ecological Applications*. doi: 10.1890/09-0838.
- Shafii R, Price WJ, Prather TS, Lass LW and Thill DC (2003) Predicting the likelihood of yellow starthistle (*Centaurea solstitialis*) occurrence using landscape characteristics. *Weed Science* **51**, 748–751.
- Sharov A and Liebhold AM (1998). Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecological Applications* **8**(3), 833–845.
- Sharov AA, Liebhold AM and Roberts EA (1998) Optimizing the use of barrier zones to slow the spread of gypsy moth (Lepidoptera: Lymantriidae) in North America. *Journal of Economic Entomology* **91**(1), 165–174.
- Shaw DR (2005) Translation of remote sensing data into weed management decisions. *Weed Science* **53**, 264–273.
- Sindel BS, van der Meulen A, Coleman M and Reeve I (2008) *Pathway risk analysis for weed spread within Australia*, Final Report to Land and Water Australia (UNE61), University of New England, Australia, 107p.
- Sinden JA and Thampapillai DJ (1995) Introduction to benefit-cost analysis, Longman, Melbourne, pp 262.
- Smith DR, Villella RF and LeMarié DP (2003) Application of adaptive cluster sampling to low-density populations of freshwater mussels. *Environmental and Ecological Statistics* **10**, 7–15.
- Smolik MG, Dullinger S, Essl F, Kleinbauer I, Leitner M, Peterseil J, Stadler LM and Vogl G (2010) Integrating species distribution models and interacting particle systems to predict the spread of an invasive alien plant. *Journal of Biogeography* **37**, 411–422.
- Solow AR 1993. Inferring extinction from sighting data. *Ecology* **74**, 962.
- Solow AR 2005. Inferring extinction from a sighting record. *Mathematical Biosciences* **195**, 47–55.
- Solow A, Seymour A, Beet A and Harris S (2008) The untamed shrew: on the termination of an eradication programme for an introduced species. *Journal of Applied Ecology* **45**, 424–427.
- Steele K, Carmel Y, Cross J and Wilcox C (2008) *Uses and misuses of multi-criteria decision analysis (MCDA) in environmental decision-making*. Final Report, ACERA Project 0607 and 0610, University of Melbourne, 19pp.
- Steele K, Carmel Y, Cross J and Wilcox C. (2009) Uses and misuses of multi-criteria decision analysis (MCDA) in environmental decision-making. *Risk Analysis* **29**, 26–33.
- Taylor CM and Hastings A (2004) Finding optimal control strategies for invasive species: a density-structured model for *Spartina alterniflora*. *Journal of Applied Ecology* **41**, 1049–1057.
- The Mathworks (2002). *Using MATLAB*. Natick, MA, USA.
- Thomas N, Steel J, King C, Hunt T and Weiss J (2007) *Tackling weeds on private land initiative: weed spread pathway risk assessment – stage 2*, Department of Sustainability and Environment, Department of Primary Industries, Victoria.
- Thomas L, Buckland ST, Rexstad EA, Laake JL, Strindberg S, Hedley SL, Bishop JRB, Marques TA and Burnham KP (2010) Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology* **47**, 5–14.
- Turchin P and Odendaal FJ (1996) Measuring the effective sampling area of a pheromone trap for monitoring population density of southern pine beetle (*Coleoptera: Scolytidae*). *Environmental Entomology* **25**, 582–588.

- Turk P and Borkowski JJ (2005) A review of adaptive cluster sampling: 1990-2003. *Environmental and Ecological Statistics* **12**, 55–94.
- Tyre AJ, Tenhumberg B, Field SA, Niejalke D, Parris K and Possingham HP (2003) Improving precision and reducing bias in biological surveys: estimating false-negative error rates. *Ecological Applications* **13**, 1790–1801.
- Václavík T and Meentemeyer RK, (2009) Invasive species distribution modeling (iSDM): Are absence data and dispersal constraints needed to predict actual distributions? *Ecological Modelling* **220**, 3248–3258.
- van der Kraan C and van Deventer P (1982). Range of action and interaction of pheromone traps for the summerfruit tortrix moth, *Adoxophyes orana* (F.v.R.). *Journal of Chemical Ecology* **8**, 1251–1262.
- Vogt JT and Wallett B (2008) Feasibility of using template-based and object-based automated detection methods for quantifying black and hybrid imported fire ant (*Solenopsis invicta* and *S. invicta* x *richteri*) mounds in aerial digital imagery. *The Rangeland Journal* **30**: 291-295.
- Vrbova L, Stephen C, Kasman N, Boehnke R, Doyle-Waters M, Chablitt-Clark A, Gibson B, Brauer M and Patrick D (2009) *Systematic review of surveillance systems for emerging zoonotic diseases*.  
<[http://www.nccch.ca/files/Zoonoses\\_Surveillance\\_May\\_2009.pdf](http://www.nccch.ca/files/Zoonoses_Surveillance_May_2009.pdf)>
- Wall C and Perry JN (1978) Interactions between pheromone traps for the pea moth, *Cydia nigricana* (F.). *Entomologia Experimentalis et Applicata* **24**, 155–162.
- Ward FA (2006) *Environmental and natural resource economics*. Pearson Prentice Hall, New Jersey.
- Wenger SJ and Freeman MC (2008) Estimating species occurrence, abundance, and detection probability using zero-inflated distributions. *Ecology* **89**, 2953–2959.
- Wikle CK and Royle JA (1999) Space-time dynamic design of environmental monitoring networks. *Journal of Agricultural, Biological, and Environmental Statistics* **4**(4): 489-507.
- Williams NSG, Hahs AK and Morgan JW (2008) A dispersal-constrained habitat suitability model for predicting invasion of alpine vegetation. *Ecological Applications* **18**, 347–359.
- Wintle BA, McCarthy MA, Parris KM, Burgman MA (2004) Precision and bias of methods for estimating point survey detection probabilities. *Ecological Applications* **14**, 703–712.
- Worner SP and Gevrey M (2006) Modelling global insect pest species assemblages to determine risk of invasion. *Journal of Applied Ecology* **43**, 858–867.
- WTO (World Trade Organisation) (n.d.). *Technical Information on Technical barriers to trade*.  
[http://www.wto.org/english/tratop\\_e/tbt\\_e/tbt\\_info\\_e.htm](http://www.wto.org/english/tratop_e/tbt_e/tbt_info_e.htm).
- WTO (1998). *Understanding the WTO Agreement on Sanitary and Phytosanitary Measures*.  
[http://www.wto.org/english/tratop\\_e/sps\\_e/spsund\\_e.htm](http://www.wto.org/english/tratop_e/sps_e/spsund_e.htm).
- Yackel Adams AA, Stanford JW, Wiewel AS and Rodda GH (2010) Modelling detectability of kiore (*Rattus exulans*) on Aguiuan, Mariana Islands, to inform possible eradication and monitoring efforts. *New Zealand Journal of Ecology* **34**(4).
- Yokomizo H, Possingham HP, Thomas MB and Buckley YM (2009). Managing the impact of invasive species: the value of knowing the density-impact curve. *Ecological Applications* **19**(2), 376–386.
- Zonneveld C, Longcore T and Mulder C. (2003) Optimal schemes to detect the presence of insect species. *Conservation Biology* **17**(2): 476-487.

## 9. Appendix

ACERA has invested in several projects that have developed methods and tools for improving post-border surveillance and monitoring systems, and we give additional detail about these projects in Table 10. Additional information on the outputs of each report can be found on the ACERA website: <http://www.acera.unimelb.edu.au/materials/>

**Table 10. ACERA projects of relevance to post-border surveillance.**

Project #	Author (s)	Title of Report	Additional outputs
ACERA 0604	Cindy Hauser, Peter Baxter, Tracy Rout, Michael McCarthy, Hugh Possingham	Optimal allocation of resources to emergency response actions for invasive species	Hauser and McCarthy (2009); Hauser (2009), Rout <i>et al.</i> (2009a, b)
ACERA 0605	David Fox	Statistical methods for biosecurity monitoring and surveillance	
ACERA 0607	Katie Steele, Yohay Carmel, Jean Cross and Chris Wilcox	Misuses of Multi-Criteria Decision Analysis (MCDA) in Environmental Decision making	Steele <i>et al.</i> (2009)
ACERA 0703	Tony Martin	Combining disparate data sources to demonstrate pest/disease status	
ACERA 0803	David C Cook, Shuang Liu and Wendy L. Proctor	Deliberative Methods for Assessing Utilities	Cook and Proctor (2007)
ACERA 0806	Oscar Cacho, Susan Hester and Daniel Spring	Application of search theory to invasive species control programs	Cacho <i>et al.</i> (2010); Cacho and Hester (in press); and Hester and Cacho (in press)
ACERA 0807	Greg Hood, Tony Martin, Simon Barry	Alternative methodologies for establishing pest and disease freedom	Hood <i>et al.</i> (2009)
ACERA 0809	Rochelle Christian	Community of Practice for Structured Decision making. Phase II.	
ACERA 0902	Iadine Chadès	Strategies for managing invasive species in space: deciding whether to eradicate, contain or control	
ACERA 0906	Georgia Garrard, Sarah Bekessy, Brendan Wintle	Determining necessary survey effort to detect invasive weeds in native vegetation communities	Garrard <i>et al.</i> (2008)