Report Cover Page

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Title
A review of current methods and tools used by biosecurity agencies to estimate consequence impacts on primary production, amenity, and the environment
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Summary

This report explores improved methods for characterising consequences in the context of biosecurity decision support. It reviews current approaches used to prioritize biosecurity resources, focusing especially on the criteria used to characterise consequence and the way in which they are combined. Six limitations are identified in current decision support protocols:

1. Vague formulation of the decision problem
2. Vague use of language
3. Poor estimation of likelihood in the prediction of expected consequences
4. Confusing means and ends objectives
5. Assigning arbitrary value judgments (or avoiding value judgments altogether)
6. Reluctance to include uncertainty

A prototype framework that seeks to address these limitations is outlined. The framework is built on theories of subjective expected utility and multi-attribute value, providing a structured means for coherently combining subjective predictions of cause-and-effect elicited from experts and the value judgments of decision-makers. It accommodates the market and non-market impacts of pest invasion. It has the potential to provide operational meaning to the concept of 'risk return' across the biosecurity continuum. The framework comprises five essential steps:

Step 1 Define the decision frame
Step 2 Define objectives and performance measures
Step 3 Develop alternatives
Step 4 Estimate consequences
Step 5 Evaluate trade-offs and select an alternative

The report illustrates conceptual application of the framework in three biosecurity settings: (a) prioritising pests; (b) assessing the merit of alternative actions; and (c) conducting pest risk assessments under international rules governing trade.

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A review of current methods and tools used by biosecurity agencies to estimate consequence impacts on primary production, amenity, and the environment

ACERA 1002

Improved biosecurity decision-making through better characterization of consequences.

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Executive Summary

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1.0 INTRODUCTION

Risk analysis encourages decision-making on the basis of *expected* consequences. That is, the calculation of risk as the product of likelihood and consequence is essentially an estimate of expected (dis)utility (Savage 1954). While consideration of adverse consequences alone will often suggest the desirability of avoidance or mitigation measures, conditioning estimates of consequence with assessment of likelihood may imply that such measures are not warranted. If estimates of likelihood and consequence are unbiased, then decisions based on risk should lead to more effective allocation of resources.

Risk-based decisions are common across the biosecurity continuum. Examples include:

Pre-border

- Does import of a commodity pose a risk greater than the 'appropriate level of protection' (ALOP)? If not, can we specify 'measures that would reduce the risk so that it satisfies ALOP?
- To what extent should we invest in International surveillance and intelligence gathering?
- Should we contribute to eradication and control efforts in neighbouring countries, including training of trading partner countries in biosecurity preparedness?

Border

- How should we allocate inspection resources across exposure pathways? Which airports and seaports should be targeted for inspection? Which commodities should be targeted? To what extent?

Post border

- How much effort should be dedicated to active post-border surveillance (e.g. trapping seeds or spores)?
- Can community-based surveillance be considered adequate?
- Should we pursue an eradication policy or are we better served to just contain an outbreak?
- If we adopt a containment policy for any single pest, what mix of strategies should we implement?
- On what basis can we apportion the costs of management according to public and private interests?

General

- What are high priority pests?
    - Among invertebrates?
    - Among fungi?
    - Among viruses?
    - Among pests that impact freshwater systems?
    - Among pests that impact marine systems?
    - Among forested ecosystems? etc...

This report reviews the estimation of expected consequences in biosecurity decision-making and develops a framework for improvement. We do not seek to directly address nuances associated with the range of decision problems listed above. Rather, we emphasise how estimates of expected consequence obtained through risk analysis can be used in effective decision-making in a subset of more generic problems. As a first step, we sketch two coarse examples that outline concepts underpinning the use of expected consequences in circumstances where (a) consequences are described in monetary units, and (b) consequences are described in non-commensurate units.

Decision-making on the basis of expected consequences described in monetary units

Prioritising *pests*[1] involves estimates of expected consequences in the absence of management intervention. Assessment of the merit of *actions* involves estimates of expected consequences in the presence of specified management action alternatives. For example, imagine a single pest that is currently exotic to Australia. Under a 'do nothing' scenario, the likelihood of invasion is estimated to be 0.30 over some specified time horizon. The damages resulting from invasion are estimated to be $60M. So the expected consequence for 'do nothing' is 0.30 × $60M = $18M. This expectation can be compared to that of other pests and assigned a rank priority accordingly.

Now let's say we're interested in assessing the merit of alternative actions. For simplicity, let's say there are just two alternative strategies to manage the risk posed by the pest:

A. Minimal border surveillance.
B. Additional surveillance at the border and specific control activities should the pest invade.

The likelihood of invasion under alternative A is estimated to be reduced from 0.30 to 0.25. As under the 'do nothing' scenario the damage bill if the pest invades and no control actions are undertaken is estimated to be $60M. The cost of implementing minimal border surveillance is $1M. This cost is incurred whether or not the pest invades. The table below shows possible outcomes under Alternative A.

State	**Likelihood**	**Consequence**
Invasion	0.25	$60M + $1M = $61M
No invasion	0.75	0 + $1M = $1M

Under alternative B the likelihood of invasion is estimated to be 0.10. If the pest invades control actions will limit damage to $20M. The control actions themselves cost $10M to implement. The cost of implementing additional border surveillance is $5M. The table below shows possible outcomes under Alternative B.

State	**Likelihood**	**Consequence**
Invasion	0.10	$20M + $15M = $35M
No invasion	0.90	0 + $5M = $5M

Under the axioms of subjective expected utility (Savage 1954) the decision-maker should choose the alternative that minimises expected consequence. The expected consequence of A is

[1] We use the term 'pests' in this report in a general sense, referring to any biological agent of biosecurity concern. It includes vertebrates, invertebrates, weeds, pathogens and other organisms that may cause harm to plants, animals or humans.

(0.25 × \$61M) + (0.75 × \$1M) = \$16M

The expected consequence of B is

(0.10 × \$35M) + (0.90 × \$5M) = \$8M

Both alternatives have expected consequences that are better than the 'do nothing' scenario (\$18M). Alternative B (\$8M) is better than A (\$16M).

Decision-making on the basis of expected consequences described in non-commensurate units

Real world problems are rarely so simple. Consequences are not restricted to impacts that can readily be described in monetary terms. Multiple values imply multiple objectives (Larson et al. 2011) each requiring estimates of expected consequence. For example, minimise impacts on primary production might be one objective, and minimise impacts on the natural environment might be another. All formally considered decisions involve *alternatives* and cause-and-effect *predictions* of expected consequence. When predictions are made over multiple objectives, an additional element is required to resolve the decision problem: the articulation of *preferences* reflecting the relative importance of the different objectives (Howard 2007).

For example, consider a pest prioritisation exercise. Table 1 lists four hypothetical pests and predictions of the expected consequences of establishment and spread across three values. In this case the question of which species is the highest priority is simple. Pest A is predicted to have the greatest harm to property and business, the greatest amenity impacts and the (equally) greatest environmental impacts. Identifying the second highest priority is more difficult. We need to articulate our *preferences*, the personal and social values that underpin judgments around the extent to which different impacts are tolerated or traded-off against each other. In many circumstances, individuals employed in biosecurity agencies legitimately make these value judgments as a routine part of their role. Effective decision-making demands scientific judgments concerning *predictions* of cause-and effect and social judgments that reflect our *preferences*. Both involve uncertainty.

Table 1. Four hypothetical pests and their predicted consequences. Harm to property and business is described as monetary cost, amenity impacts are described on a scale from zero (benign) to 100 (extreme severity), and environmental impacts are described using number of susceptible native species.

	Harm to property and business	Amenity impacts	Environmental impacts
Pest A	\$20M	20	4
Pest B	nil	10	1
Pest C	\$5M	nil	2
Pest D	nil	10	4

Prioritising pest species is of little use in and of itself. It says very little about the merit of any particular course of action aimed at reducing risks. Structuring decisions in a way that deals coherently with scientific judgments, value judgments, and uncertainty, and the operational setting of those responsible for biosecurity, are central themes of this report.

2.0 REVIEW OF CURRENT PROTOCOLS

In this section we review current protocols used in decision-support for biosecurity, looking at how they deal with *predictions* of expected consequence and integrate them with judgments of social *preference*.

2.1 Current protocols

The process by which many decisions are made is unstructured. The most common method of organisational decision-making is BOGSAT (Bunch of Guys/Gals Sitting Around Talking). BOGSAT may be entirely adequate for the many problems that involve small consequences. BOGSAT is not appropriate where the stakes are high. Even where detailed information and analyses are marshalled to support the meeting, BOGSAT is prey to the frailties of groupthink and deference to authority. BOGSAT meetings typically exceed the cognitive limits of the human brain. Psychologists have clearly demonstrated that our minds are incapable of processing more than about seven things at any one time. A BOGSAT discussion typically involves dozens of things, including issues, alternatives, pros, cons, objectives, criteria etc. (Forman and Selly 2001).

To the extent that they capture sound logic, structured decision protocols have advantages over BOGSAT. Apart from buffering against cognitive limitations and negative group dynamics, a documented and traceable protocol will encourage decision-makers to be clear about judgments and assumptions (Bedford and Cooke 2001). Better protocols encourage greater clarity. Below we comment on the extent to which six current protocols employed in biosecurity settings provide clarity and effective decision support. We focus especially on the criteria used to characterize consequence and the way in which they are combined.

Weed risk assessment

Pheloung et al (1999) developed a point-scoring protocol to inform border quarantine screening of potential weed species before entry to Australia. The protocol comprises 49 questions (Table 2), the responses to which contribute points to an overall score. After tallying, a high score implies a species has a high risk of becoming a weed. If a species assessment exceeds a specified threshold it is denied entry.

The protocol seeks to *predict* the relative likelihood that a plant will become a weed in Australia, but the nature of just what it means for a plant to be considered a weed is not clearly defined. Rather, the protocol is benchmarked against species that have been categorised as weeds in the past. The problem the protocol seeks to address – distinguishing weeds from non-weeds - is vaguely formulated.

The questions are more or less a series of biological cues that a group of experts identified as correlates with weediness. The value judgments (i.e. *preferences*) behind what might underpin the notion of weediness are not addressed directly. The protocol includes questions pertaining to impacts on agricultural and environmental values, based on the subjective judgement of experts. The total number of points associated with agriculture and environment is 11 and 18, respectively. It is unclear whether this represents a deliberate preferential weighting for environmental impacts or an arbitrary outcome arising from the selection and categorisation of cues.

In prediction tasks, the weighting of cues can be informed by statistical analysis or expert judgment. Multiple linear regression is a statistical additive model – it uses data to estimate weights for cues. Pheloung et al's point scoring procedure is an subjectivemodel where weights are informed by expert judgment. For most cues experts assigned equal weights in the development of the protocol because they could not invoke a factual basis for differential weights. This may seem arbitrary. But the predictive performance of subjective linear additive models is surprisingly comparable to their statistical counterparts, at least in the sociological sciences (Dawes 1979, Dana and Dawes 2004). Indeed equal weight regression performs comparably, mainly because the assumption of a fully specified model in classical regression's estimation of parameters is rarely met (Cohen 1990). It's worth noting that while the relative performance of statistical and subjective models has been found to be comparable, their absolute performance is generally modest.

Predictive performance may be improved by considering the logic of combining cues. The protocol explicitly considers the logical relationship between 'climate and distribution' and 'weed elsewhere', such that species that are climatically suited to Australia AND have been recorded as an environmental OR agricultural weed elsewhere are assigned higher weed scores. All other cues are simply added. Additive models are robust (Dawes 1979) but may not always be appropriate. For example, in order to be considered a weed a plant may need to have undesirable traits AND a niche consistent with climatic conditions in a substantial part of Australia AND reasonable capacity for dispersal. Simple addition implies OR relations between these conditions rather than AND relations. A plant may be considered highly weedy under responses made to questions 4.01 – 4.12, but be maladapted to Australian climes (2.01 – 2.05) and have poor dispersal capacity (7.01 – 7.08). The current protocol may report an intolerable weed risk for such a plant. It may be more logical to combine conditions (or a subset of them) using arithmetic operators other than addition.

Table 2. Questions contained in the weed risk assessment questionnaire. A = questions relevant to agricultural impacts, E = questions relevant to environmental impacts, C = questions relevant to agriculture and the environment combined (Source: Pheloung et al. 1999).

A C C	1	Domestication/ cultivation	1.01 Is the species highly domesticated 1.02 Has the species become naturalised where grown 1.03 Does the species have weedy races
  C C 	2	Climate and Distribution	2.01 Species suited to Australian climates 2.02 Quality of climate match data 2.03 Broad climate suitability (environmental versatility) 2.04 Native or naturalised in regions with extended dry periods 2.05 Does the species have a history of repeated introductions outside its natural range
C E A E 	3	Weed elsewhere	3.01 Naturalised beyond native range 3.02 Garden/amenity/disturbance weed 3.03 Weed of agriculture/horticulture/forestry 3.04 Environmental weed 3.05 Congeneric weed
A C C A C C C E E E E E	4	Undesirable traits	4.01 Produces spines, thorns or burrs 4.02 Allelopathic 4.03 Parasitic 4.04 Unpalatable to grazing animals 4.05 Toxic to animals 4.06 Host for recognised pests and pathogens 4.07 Causes allergies or is otherwise toxic to humans 4.08 Creates a fire hazard in natural ecosystems 4.09 Is a shade tolerant plant at some stage of its life cycle 4.10 Grows on infertile soils 4.11 Climbing or smothering growth habit 4.12 Forms dense thickets
E C E C	5	Plant type	5.01 Aquatic 5.02 Grass 5.03 Nitrogen fixing woody plant 5.04 Geophyte
C C C C C C C	6	Reproduction	6.01 Evidence of substantial reproductive failure in native habitat 6.02 Produces viable seed 6.03 Hybridises naturally 6.04 Self-fertilisation 6.05 Requires specialist pollinators 6.06 Reproduction by vegetative propagation 6.07 Minimum generative time
A C A C E E C C	7	Dispersal mechanisms	7.01 Propagules likely to be dispersed unintentionally 7.02 Propagules dispersed intentionally by people 7.03 Propagules likely to disperse as a produce contaminant 7.04 Propagules adapted to wind dispersal 7.05 Propagules buoyant 7.06 Propagules bird dispersed 7.07 Propagules dispersed by other animals (externally) 7.08 Propagules dispersed by other animals (internally)
C A A C E	8	Persistence attributes	8.01 Prolific seed production 8.02 Evidence that a persistent propagule bank is formed (>1 yr) 8.03 Well controlled by herbicides 8.04 Tolerates or benefits from mutilation, cultivation or fire 8.05 Effective natural enemies present in Australia

Vertebrate risk assessment

Bomford (2008) also used a point-scoring procedure in development of a vertebrate risk assessment protocol that captured the views of members of the Vertebrate Pests Committee (VPC). The decision frame is pre-import screening of potential vertebrate pests before entry to Australia (i.e. the same context as Pheloung et al's risk assessment, but for vertebrates instead of weeds). Bomford (2008) developed similar protocols for exotic mammals and birds, reptiles and amphibians, and freshwater fish. The exact criteria varied with taxonomic group. The criteria for exotic mammals and birds are shown in Table 3.

Criteria are split into three groups – (A) risks posed by captive or released individuals, (B) risk of establishment, and (C) risk of becoming a pest. In each group simple weighted summation is again used (equivalent to an improper predictive model) to provide an ordinal class of risk (low, moderate, high or extreme). Part B can reasonably be interpreted as likelihood and Part C as consequence. The outcomes of assessment within the three groups are combined using the risk matrix shown in Table 4 to give an overall threat category for the vertebrate being assessed.

Formulation of the problem in the vertebrate protocol is somewhat clearer than that for weeds. There is a logical structure to the prediction of expected consequence in the combination of B (likelihood) and C (consequence) in the risk matrix (Table 4). There are elements of the fundamental values of concern to us when we describe consequence (i.e. harm to people and property). Part C again includes impacts on agriculture and the environment together with harm to property and people. The overall threat categories that result from the combination of outcomes in Parts B and C suggest multiplication has been appropriately used.

Table 3. Criteria used in the Australian mammals and birds risk assessment protocol (Source: Bomford 2008).

A	Risks posed by captive or released individuals	A1. Risk to people from escapees A2. Risk to public safety from individual captive animals
B	Risk of establishment	B1. Climate match B2. Exotic population established overseas B3. Overseas range size B4. Taxonomic class B5. Diet breadth B6. Habitat breadth B7. Migration
C	Risk of becoming a pest	C1. Taxonomic group C2. Overseas range size C3. Diet and feeding C4. Competition with native fauna for tree hollows C5. Overseas environmental pest status C6. Climate match to areas with susceptible native species or communities C7. Overseas primary production pest status C8. Climate match to susceptible primary production C9. Spread disease C10. Harm to property C11. Harm to people

Table 4. Matrix for assigning threat category from outcomes of the point scoring questionnaire summarised in Table 3. (Source: Bomford 2008).

Establishment risk (B)	Pest risk (C)	Risk posed by individual escapees (A)	Threat category
Extreme	Extreme	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
Extreme	High	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
Extreme	Moderate	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
Extreme	Low	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
High	Extreme	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
High	High	Highly Dangerous, Moderately Dangerous or Not Dangerous	Extreme
High	Moderate	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Serious
High	Low	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Serious
Moderate	Extreme	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Extreme
Moderate	High	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Serious
Moderate	Moderate	Highly Dangerous	Serious
Moderate	Moderate	Moderately Dangerous Or Not Dangerous	Moderate
Moderate	Low	Highly Dangerous	Serious
Moderate	Low	Moderately Dangerous Or Not Dangerous	Moderate
Low	Extreme	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Serious
Low	High	Highly Dangerous, Moderately Dangerous Or Not Dangerous	Serious
Low	Moderate	Highly Dangerous	Serious
Low	Moderate	Moderately Dangerous Or Not Dangerous	Moderate
Low	Low	Highly Dangerous	Serious
Low	Low	Moderately Dangerous	Moderate
Low	Low	Not Dangerous	Low

The logic behind other aspects of the protocol is difficult to comprehend. The inclusion of predictive cues (e.g. overseas range size; diet and feeding) with social values (e.g. harm to property; harm to people) in Part C confuses means and ends. That is, it conflates the task of scientific prediction with judgments concerning societal preferences. It suggests some confusion among members of the VPC in disentangling means and ends.

Another weakness is the language based ambiguity in characterisation of likelihood and consequence as ‘low’ ‘moderate’, ‘high’ and ‘extreme’. VPC may regard these descriptors as appropriately ambiguous given the uncertainty embedded in judgments. Hubbard (2009) describes the common tendency to view ambiguity as an offset to uncertainty. But the verbal descriptors are subject to variable interpretation with respect to absolute expected consequences (Regan et al. 2002). In introduces another source of error rather than offset uncertainty.

The weed and vertebrate risk assessment protocols reflect the disciplinary background of those responsible for their development. They emphasise biological cues and their correlations with weeds and pests that have established in the past. When combined logically as improper models, these cues can provide reasonable *predictions*. But while biological cues tell us something of scientific cause-and-effect, they are of little relevance to the capture of social *preferences*. Social preferences require value judgments not technical judgments.

Pest categorisation

Once a weed or other pest has entered or established in Australia, it may be 'categorised' to decide cost-sharing arrangements between the public and private sectors. The Emergency Plant Pest Response Deed includes four categories:

Category 1	Very high public benefits	100% public funding
Category 2	High public benefits	80/20 split public/private
Category 3	Moderate public benefits	50/50 split public/private
Category 4	Mostly private benefits	20/80 split public/private

The perceived legitimacy of cost-sharing arrangements rests on the protocol's capacity to characterise the absolute and relative expected consequences for private and public values. The protocol comprises three elements: (a) a decision tree (Figure 1) (b) a point scoring questionnaire with coarse ordinal responses, completed by multiple experts (Table 5) and (c) subsequent BOGSAT discussion guided by the decision tree, pooled questionnaire scores, and any other relevant information.

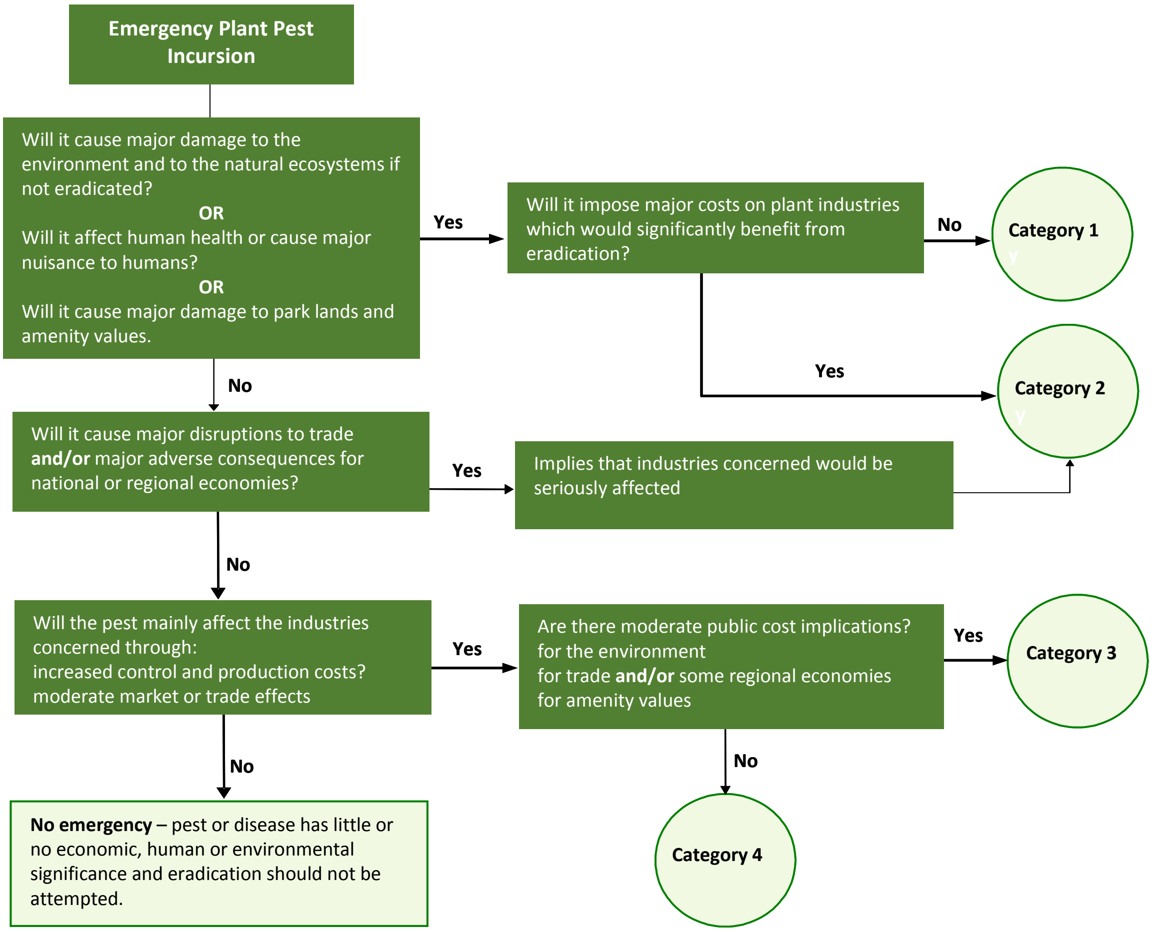


Figure 1. Decision tree used for plant pest categorisation. (Source: PHA (2010)).

The impact descriptors of responses from the questionnaire logically map onto the decision tree. The protocol's principal weakness is language-based ambiguity regarding what magnitude of impact is considered ‘major’, ‘moderate’ or ‘minor’. Assessors completing the questionnaire in Table 5 will tend to conflate their predictions of impact with value judgments of the importance of those impacts. It is possible that two or more assessors agree on the magnitude of impact on say public amenities and parkland (Q3) but enter entirely different responses because they hold different value judgment concerning the importance of public amenities and parkland. To more effectively support decision-making the separate tasks of making predictions and articulating preferences need to be disentangled

Table 5. Questionnaire used for plant pest categorisation. Responses inform the appropriate pathway in the decision tree shown in Figure 1. (Source: PHA (2010)).

Question	**Responses**
1. The impact of the pest on the environment and natural ecosystems would be:	Major Moderate Minor or no impact
2. The impact of the pest on human health and lifestyle would be:	Major Moderate Minor or no impact
3. The impact of the pest on public amenities and/or parklands would be:	Major Moderate Minor or no impact
4. The direct impact on industry net returns would be: The answer to this question is derived through supplementary questions exploring • availability of resistant varieties or germplasm • availability of chemical control • registration status of chemicals • future prospects for chemical control availability • whether the pest kills the plant • whether presence of the pest reduces or causes production to cease • additional costs incurred to make the product marketable	Major Moderate Minor or no impact
5. The presence of the pest in Australia would result in market/trade restrictions with:	The majority of trading partners Some trading partners No trading partners
6. Would the presence of the pest cause indirect (flow-on) effects to other industries or other sectors be: The answer to this question is derived through supplementary questions exploring • whether importation of the commodity into Australia is restricted • geographically isolation of commodity production	Large Equivalent Small
7. Will the presence of the pest impose significant social adjustment costs to regional communities? The answer to this question is derived through supplementary questions exploring • geographic concentration of the industry • significance of the direct industry as a regional employer • significance of any value-adding industry as a regional employer • mobility of affected employees • flow-on effects of relocating employees on regional services	Yes No

Pathogens and Invertebrates

Raphael et al. (2009) developed a method for prioritising exotic terrestrial and freshwater pathogens and invertebrates for use by an environmental management agency. The context was drafting a list of species whose potential environmental impacts could be considered nationally significant. Its environmental emphasis sought to address a perceived bias in existing lists and databases towards species of significance to primary production and trade. The time available to develop and test the method was severely constrained.

The method comprised several sequential steps:

1. Screening existing lists
2. Creation of a preliminary list using informal aggregation of invasion potential questions derived from Bomford (2008) and Brown (2007) and AusBIOSEC criteria[2].
3. Refinement and shortlisting using simple weighted summation Multicriteria decision analysis (MCDA).

Step 3 essentially formalised aggregation of the criteria employed in Step 2. The criteria used are shown in Table 6. The weights assigned to criteria a - g (invasion potential and environmental impacts) were four times greater than h (impacts on people) and i (impacts on business).

Table 6. Criteria and sub-criteria used to prioritise pathogens and invertebrates (Source: Raphael et al. 2009).

Criteria	**Sub-criteria**
Invasion potential	a. Proximity to Australia b. Invasiveness elsewhere c. Host specificity d. Geographic distribution e. Introduction pathway (regulated and/or unregulated) f. Propagule pressure (Introduction risk)
AusBIOSEC criteria	g. Environmental impacts • Impacts on nationally important species • Impacts on ecologically valuable species • Impacts on nationally important places • Impacts on ecologically important places • Extensive impacts h. Impacts on people • Impacts on public health • Impacts on human infrastructure • Impacts on public amenity • Cultural impacts i. Business impacts • Substantial increases in business costs • Substantial loss of production or business opportunity

[2] Note that the AusBIOSEC criteria have subsequently been revised. See IGA (2009) and Figure 3 of this report.

The AusBIOSEC criteria comprise a reasonably coherent set of values for assessing consequence (although there may be some redundancy). Likewise, the cues listed under 'invasion potential' might be considered a reasonable basis for a weighted improper model to predict likelihood. But simple weighted summation of the likelihood cues and consequence criteria is nonsensical. Expected consequence is the product of likelihood and consequence, not the sum.

A four-fold weighting on environmental impacts may be a reasonable and informed value judgment, especially given the end user's motivation to redress perceived bias in existing lists and databases towards species of significance to primary production and trade. But it is unclear what logic could underpin invasion potential being given a four-fold weighting relative to impacts on people or businesses, when its causal contribution to expected consequences for the environment, people and business is equal. Again, the confusion of cues for prediction and criteria representing value judgments leads to a confounding of means and ends, and of predictions and preferences.

Raphael et al. (2009) acknowledge that simple weighted summation may not be appropriate for the criteria used in their protocol. The authors present their method as a work in progress, and highlight the need to consult with stakeholders in revisiting the value judgments made in the MCDA, among other areas for improvement.

Prioritization of Phytophthora of concern to the United States

Like Raphael et al.'s pathogens and invertebrates protocol, Schwartzburg et al. (2009) employed MCDA to rank 29 *Phytophthora* species and subspecies currently not established in the US. The aim of the ranking was to target detection and regulation effort. The criteria used in their analysis are shown in Table 7 below.

The anticipated impacts of each of the 29 taxa were scored against each of the criteria using coarse ordinal response classes. Criteria weights were then derived using the Analytic Hierarchy Process (AHP), whereby matrix computations are used to transform pairwise judgments of the relative importance of criteria (Saaty 1980).

The most striking deficiency of the MCDA is the complete absence of any consideration of the likelihood of invasion. The rankings based solely on consequences for the environment and economy implicitly assumes all species and subspecies have equal likelihood of entry, establishment and spread. Outcomes will lead to large opportunity costs in resource allocation, as expenditure on detection and regulation is committed to taxa characterised as having large consequences should they successfully invade, but the probability of these consequences being realised may be trivially small.

Table 7. Criteria used to rank Phytophthora species and subspecies according to the threat they pose to the Unites States (Source: Schwartzburg et al. 2009).

Criteria	Sub-criteria
Environmental Impact	*Ecosystems* Ecological damage caused by the pathogen's establishment throughout its potential range
	Threatened or endangered species Establishment of the pathogen throughout its potential range will have a negative effect on threatened or endangered species
	Health of plants with aesthetic value The degree to which the pathogen's establishment throughout its potential range will endanger plants that have value beyond commercial production (e.g., cultural significance, medicinal uses, tourism)
Economic Impact	*Foreign trade* Establishment of the pathogen in its potential range will have a negative impact on foreign trade
	Production costs and domestic trade Establishment of the pathogen in its potential range will have a negative impact on production costs and domestic trade
	Public costs Establishment of the pathogen in its potential range will have a negative impact on public costs.

A lesser (but still substantial) concern is the way weights were derived. A team of plant pathologists weighted environmental impact 0.55 and economic impact 0.45 using AHP. There are very good reasons for engaging experts in the task of *prediction*, but there is no reason to believe they offer any advantages over non-experts and stakeholders in the articulation of *preferences*.

Use of AHP as a method for weighting is not highly recommended. 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 in the context of the objects being considered (i.e. *Phytophthora* species and subspecies in this case) (Fischer 1995). A common mistake is to weight only on the basis of importance. The pairwise comparisons used in AHP do not make the range of consequences salient to decision makers (see Steele et al. 2009 and the Appendix of this report).

Finally, there is once again evidence of some confusion in means and ends objectives. The economic criterion includes sub-criteria that translate to sub-objectives of minimising impact on 'foreign trade', and minimising impact on 'production costs and domestic trade'. These sub-objectives are means to the fundamental end of minimising impact on the private sector. The inclusion of means objectives tends toward double counting. When simple weighted summation is used in MCDA, criteria should reflect only fundamental (ends) objectives (see Appendix).

Pre-border: import risk analyses

Plant import risk analysis

Biosecurity Australia's pest risk analysis protocol (Biosecurity Australia 2009) seeks to characterise risk in the context of allowing or disallowing import of a new commodity. Risk is the product of likelihood and consequence, each of which is described using ordinal classes. A commodity is allowed if it satisfies Australia's appropriate level of protection, equivalent to a verbal descriptor of 'very low' risk (Table 8).

For assessments of plant material, likelihood is the product of individual judgments of the probability of

- entry (comprising the product of the probabilities of importation and distribution),
- establishment, and
- spread.

That is, likelihood is the probability of entry AND establishment AND spread (EES). Although ordinal classes of Pr{EES} are used, a corresponding numerical scale exists so that bias and error arising from variable interpretations of the language, 'negligible', 'very low', 'moderate' etc. is avoided.

For consequence, six criteria are assessed assuming EES:

- Direct impacts on plant life or health
- Impacts on international trade
- Impacts on domestic trade
- Direct impacts on other aspects of the environment
- Indirect impacts on the environment
- Costs of eradication and control

Relative to likelihood, characterisation of the magnitude of consequence under each criterion is opaque. The scale and intensity of estimated impact informs designation of an impact factor, A (lesser consequence) to G (greater consequence). The scale (and units) of 'A' - 'G' is unspecified. IF-THEN rules combining impact factors across criteria are then used to assign an overall consequence descriptor – 'negligible', 'very low', 'low', 'moderate', 'high' or 'extreme'. It is unclear whether the rules are based on simple summation of criterion-specific impacts or some other arithmetic operation.

The protocol could be interpreted as weighting each criterion equally. This is true in the sense that impact factors A – G are treated equally in the configural rules irrespective of the specific criteria involved. But weighting should reflect the magnitude of the range of impacts associated with A - G. Ranges are undefined, leaving the protocol prey to the variable value judgments of individual assessors. Effectively, weights depend on the submerged judgments of assessors.

Table 8. Risk matrix used in Biosecurity Australia's pest risk analysis. Likelihood is interpreted as the probability of entry and establishment and spread. Australia's appropriate level of protection is 'very low'. The import of commodities with potential pests considered higher risk is disallowed (Source: Biosecurity Australia 2009).

Pr{EES}	***high***	negligible	very low	low	moderate	high	extreme
	moderate	negligible	very low	low	moderate	high	extreme
	low	negligible	negligible	very low	low	moderate	high
	very low	negligible	negligible	negligible	very low	low	moderate
	extremely low	negligible	negligible	negligible	negligible	very low	low
	negligible	negligible	negligible	negligible	negligible	negligible	very low
		negligible	***very low***	***low***	***moderate***	***high***	***extreme***
		Consequence					

The logic of combining likelihood and consequence is sound and the most transparent of the protocols reviewed here. The combination of the judgments that make up Pr{EES} make probabilistic sense, and their combination with the verbal descriptors of consequence can be coarsely interpreted as expected consequence (i.e. the product of likelihood and consequence).

However the protocol fails to consider impacts that might arise prior to spread. It's not difficult to imagine scenarios where pests need only enter or establish (and not spread) for non-trivial impacts to be seen in control costs, or domestic and international trade. Failure to consider the likelihood and consequences of states other than EES results in systematic underestimation of risk.

Similar to the *Phytophthora* protocol, the pest risk assessment's consequence criteria confuse means and ends objectives. Impacts on plant life and health are not of fundamental concern in and of themselves. Minimising these impacts is a means of serving the more fundamental objectives of minimising impacts on the environment, business and the public costs of eradication and control. Including both these means and ends clearly leads to double counting.

Animal import risk analysis

The structure of the protocol for assessment of animals, animal products and genetic material is slightly different. The risk posed by any particular hazard (typically a disease) is characterised as the

likelihood of release AND exposure × expected consequence.

'Expected consequence' refers to the outcome of scenario analyses that countenance outcomes at the point of establishment OR spread. Consequences are estimated against seven criteria using the same descriptors employed in the plant protocol. That is, the scale and intensity of estimated impact informs designation of an impact factor, A (lesser consequence) to G (greater consequence). The aggregation of impacts across the seven criteria also use IF-THEN rules to arrive at an overall consequence descriptor of 'negligible', 'very low', 'low', 'moderate', 'high' or 'extreme'. Six of the seven criteria are essentially the same as those invoked in plant assessments (with the first criterion referring to impacts on animal life or health rather than plant life or health). The additional seventh criterion refers to impacts on 'communities, including reduced tourism, reduced rural and regional economic viability and loss of social amenity, and any side effects of control measures' (Biosecurity Australia 2010).

The animal protocol is better than the plant protocol in two aspects. Firstly, it can accommodate an assessment of impacts at the point of establishment, prior to spread (although it does not explicitly deal with impacts at the point of entry). Secondly, its specific inclusion of social impacts and side effects of control measures as a separate criterion provides a more complete assessment of consequences.

It also has weaknesses in common with the plant protocol. The scale and units of consequence descriptors 'A' - 'G' are again unspecified, suggesting assessors will vary in the assignment of impact according to their personal value judgments. Again, there is considerable overlap in criteria which may lead to double counting, despite explicit instruction for assessors to treat the seven classes of consequence as mutually exclusive.

2.2 Limitations of decision support protocols

This review has focussed on limitations of current protocols in the context of formal decision theory. Theoretical limitations need not imply strikingly poor performance. For example, the practice of weighting and summing relevant factors may be robust (in the sense that they can provide coarse but useful predictions) even if those factors include elements associated with likelihood and consequence (for which the product rather than the sum is more valid). Many regression techniques are built on a model of simple summation (Dawes 1979, Cohen 1990). Using an analogy from physics, we might estimate force using the sum of mass and acceleration. Certainly the sum will be correlated with force, but Newton tells us that force is *equal* to the product of mass and acceleration. The weed risk assessment' summation protocol (Pheloung et al. 1999) has been shown to be a good discriminator of weeds and non-weeds using independent data sets in Australia and overseas (Hughes and Madden 2003, Gordon et al. 2008).

The 'limitations' listed here may not be critical. We identify them in the hope that effective remedies that appeal to coherent theory will offer substantial improvements to biosecurity decision-making.

We identify six main limitations commonly evident in current decision support protocols.

Limitation 1: Vague formulation of the decision problem

All of the biosecurity decision problems explored in section 2.1 require predictions of expected consequence and the articulation of preferences over multiple objectives. Predictions entail judgments of likelihood and consequence, and their multiplication. Preferences involve the assignment of weights to fundamental objectives. None of the protocols examined coherently combine these core elements.

Limitation 2: Vague use of language

Language-based ambiguity is an arbitrary source of uncertainty (Regan et al. 2002). The pest categorisation protocol could be substantially improved by simply defining the magnitude of impact meant by the term 'major' in the various contexts in which it is used in the decision tree designed to guide cost sharing arrangements (Figure 1). Likewise, the pre-border pest risk assessment protocol would benefit from clear description of what is meant by each impact factor 'A' to 'G' under each consequence criterion. Wherever possible, direct, measurable and understandable attributes should be used to describe expected consequences against each objective or criterion (Keeney and Gregory 2005).

Limitation 3: Poor estimation of likelihood in the prediction of expected consequences

Likelihood is a necessary component of the estimation of expected consequence by definition. Failure to include likelihood will result in misallocation of resources. People (experts included) tend to overestimate the likelihood of rare events and underestimate the likelihood of common events (Fischoff et al. 1982). Verbal descriptors of likelihood may exaggerate this tendency to compress (Cox et al. 2005). Numerical characterisation of likelihood provides greater clarity. Improper models that combine cues for likelihood provide only relative scores, requiring calibration and rescaling to the interval [0,1] if they are to be used in quantitative descriptors of expected consequence. Finally, different decision contexts may require different estimates of likelihood. The probability of entry AND establishment AND spread may not be the only relevant state in the estimation of expected consequence (see Figure 4).

Limitation 4: Confusing means and ends objectives

The most common problem with using simple weighted summation in decision support protocols involving multiple values is inclusion of *means* objectives in the set of concerns. For example, traffic authorities may seek to minimise speeding and minimise drink-driving. These are means for achieving the fundamental objective of minimising fatalities. Similarly, the objectives of a quarantine service may include maximising the number of incursions detected or maximising deterrence. But the fundamental ends objectives are to minimise harm to business, the environment, public health and amenity. Means objectives lead to double counting or violation of the assumption of mutual preference independence (Keeney and von Winterfeldt 2007; see Appendix). Identification of a set of fundamental ends objectives is not as simple as it may seem (Bond et al. 2008), but techniques exist to do so (Failing et al. 2007).

Limitation 5: Assigning arbitrary value judgments (or avoiding value judgments altogether)

The weights assigned to fundamental objectives should reflect the preferences of decision maker(s) acting on behalf of an organisation or broader society. These preferences should be sensitive to the range of consequences specific to the alternatives available in any given decision context, not just the importance of objectives, free of context. Where consequences are not explicitly described (such as in the pre-border pest risk assessment protocol) weights are essentially arbitrary. Likewise, weights assigned to objectives criteria (e.g. harm to property or people) are more or less meaningless if they are lumped with predictive cues or overlapping concerns (e.g. Part C of the vertebrate risk assessment protocol; Table 3).

Limitation 6: Reluctance to include uncertainty

Many protocols specify crisp categorical or ordinal responses to questions or criteria. For example, the yes/no structure of Pheloung et al's (1999) weed risk assessment, or the major/moderate/minor responses in the weed categorisation questionnaire (Table 5). As highlighted above, the categories suffer from language-based ambiguities, but even if these were to be resolved there will be borderline cases. People will hold degrees of belief (rather than absolute beliefs) in the extent to which a species falls into one or more categories. More generally, estimates of the probability of entry, establishment and spread, and the consequences should these events occur all involve uncertainty. Failure to report uncertainty imposes a risk-neutral attitude on decision-makers (see 'Uncertainty' in section 3.2 below).

2.3 Discussion

When faced with high-stakes, low probability settings decision-makers are prey to a range of biases, including (Kunreuther et al. 2002):

- under-utilization of probability information and failure to differentiate among probabilities,
- an excessive focus on short time horizons,
- excessive attention to affectual cues,
- over-reliance on social norms,
- a tendency to prefer the *status quo;* and
- failure to learn.

These biases will be most pronounced when decision-making is left to individuals. Collective decision-making offers some insulation, even if the approach used is BOGSAT. Structured protocols for decision-support may offer substantial insulation, depending on the merit of the specific protocol employed (Cox et al. 2005).

The focus of this review has been on the logic underpinning judgments of preferences and prediction, and their combination. We have said little about how to capture those judgments themselves. Section 3.0 below presents a method for eliciting weights for the purpose of articulating preferences. A more formal method for assigning weights is outlined in the Appendix of this report.

Prediction is the domain of science. We may call on experts to provide judgments directly, or we may engage practitioners to build qualitative or quantitative models. The resources, time and effort expended in the capture of predictions represents a trade-off between effort and performance (Payne et al. 1993). An appreciation of the relative performance of various predictive models would help inform the investment of effort. But by its nature, biosecurity offers only sparse data to validate predictions of pest invasion and its consequences, making validation and performance appraisal difficult.

There are a multitude of tools and models available to predict individual elements of individual decision problems. For example, self-organising maps help predict the likelihood of entry and establishment (Gevrey et al. 2006). The spatial extent of spread can be mapped using boosted regression trees (Elith et al. 2008), among other advanced statistical tools. Market impacts can be measured and the benefits and costs of alternative actions or policies evaluated using traditional economic techniques (e.g. Cook and Fraser 2008). Non-market values can be monetised and included in cost-benefit analyses using choice modelling (Bennett and Blamey 2001). Agent-based modelling offers an innovative approach to evaluating multiple pest invasion scenarios (Elliston and Beare 2006). All of these tools and techniques vary in the time required to produce outcomes, the data needed for input, and the resourcing required in personnel and computing.

The approach adopted in the proposed framework described in the next section emphasises logic and coherence in estimating expected consequence. It borrows from accessible tools recently applied in natural resource management (Pannell et al. 2009) and conservation biology (Joseph et al. 2009) that have their origins in economic analysis and decision theory. It is less concerned with predictive accuracy.

The framework advocates routine and improved use of expert judgment for prediction tasks. In doing so it imposes a view that the perfromance-effort trade off will be favourable if better use is made of the experience and knowledge within networks of biosecurity professionals. There is little basis for this judgment. The framework will provide superior outcomes if greater investment effort produces improved predictive performance. But better information comes at a cost. Calculating the *value of information* provides a formal means of assessing whether capture of further data and analyses is worthwhile. In a decision-making context collecting more or better information is only warranted if the reduction in uncertainty changes the preferred course of action. It is possible to make optimal decisions with imperfect information. To estimate an upper bound on the benefit of more observations, the *value of perfect information* can be calculated as the mean value

$$\sum_x p(x)U(\mathbf{F}|x),$$

where the sum is over all states x, $p(x)$ is the prior probability of that state, and $U(\mathbf{F}|x)$ is the utility of the optimal decision given the state x. If the cost of making an observation is more than the saving we expect to make by getting perfect information then the observation is not worth making (Bedford and Cooke 2001).

3.0 A FRAMEWORK FOR IMPROVEMENT

Normative approaches to decision-making appeal to a set of axioms that define rational behaviour. Loosely translated, these axioms define a rational person as someone who consistently seeks to maximise a sense of well being (utility) in the choices they make. Strict use of normative methods in real-world settings can be laborious, mathematically turgid, and frustratingly opaque.

The approach to structured decision-making proposed here is *prescript*ive. It compromises normative ideals for the sake of accessibility and ease of use, while buffering against common traps in decision-making. It seeks to provide good solutions rather than optimal solutions. Its bases are the theory of subjective expected utility (Savage 1954) and multi-attribute value theory (Keeney and Raiffa 1993).

There are five iterative steps in the prescriptive approach to structured decision-making used in this report (adapted from Failing et al. 2007):

- Step 1 Define the decision frame
- Step 2 Define objectives
- Step 3 Develop alternatives
- Step 4 Estimate expected consequences
- Step 5 Evaluate trade-offs and select an alternative

Here we outline each of these steps before demonstrating their application in three broad biosecurity decision contexts. The examples include considerable detail in the calculation of expected consequence that will appeal to readers interested in how the framework can be implemented operationally. For readers interested only in a conceptual understanding, the details of these calculations can be ignored.

Step 1 Define the decision frame

There are a range of specific decision frames across the biosecurity continuum. Does a pest exceed Australia's 'appropriate level of protection (ALOP)'? If so, can we specify measures that would reduce the risk so that it meets ALOP? To what extent should we invest in international or domestic surveillance and intelligence gathering? Which imported commodities have the highest associated risk? Following pest incursion, should we attempt eradication or are we better served to invest in control? The details of each of these decision frames will be different. The biology of different pests and the dynamics of specific ecosystems need to be considered in the prediction of impacts.

The decision frame at different points along the biosecurity continuum is often shaped by administrative and organisational settings. Pre-border, the decision frame is clearly informed by international regulations, guidelines and precedent. The focus on inspection at the border makes resource allocation across multiple pathways the central frame. The post-border setting is not so clearly defined. Individual decisions around surveillance, control and eradication need to consider the time horizon over which consequences will be estimated and the preferences of stakeholders who may be required to co-contribute funding or who bear the costs of poor decision-making.

Using hypothetical pests, Section 3 explores three broad decision frames:

3.1 Prioritising pests: Which pests are highest priority with respect to the risks they pose under a 'do nothing' scenario?

3.2 Assessing the merit of alternative actions: Which strategies are most cost-efficient in the management of risks?
3.3 Regulated pathways: What measures are least trade restrictive in satisfying Australia's ALOP in the context of an import risk assessment?

Step 2 Define objectives

Defining objectives can be surprisingly difficult (Bond et al. 2008). Objectives should appeal to fundamental values that biosecurity agencies seek to protect. A common set of objectives to be applied across the biosecurity continuum is desirable for consistent resource allocation within any one agency.

The set of fundamental objectives should be complete and comprehensible (Gregory et al. 2005). Because we'll be using simple weighted summation as a model of expected consequence in our framework, the desirable properties of fundamental objectives (Keeney 2007) described in the Appendix are especially important. A common mistake is to confuse 'means objectives' with 'fundamental (ends) objectives'. Means objectives are intermediate goals that serve as stepping stones towards the things that are of fundamental concern (Keeney and Gregory 2005). Inclusion of both means and ends leads to double counting.

The examples explored in Sections 3.1 – 3.3 of our framework are incomplete with respect to fundamental objectives. We include only three fundamental objectives of biosecurity:

- Minimise adverse business impacts (measured in $M)
- Minimise adverse amenity impacts (measured on a scale from 0 to 100)
- Minimise adverse environmental impacts (measured as the number of directly susceptible native species).

We present these examples for illustrative purposes only.

A more complete set was developed at a workshop conducted as a part of ACERA 1002 (this project) in April 2010 (Table 9). These objectives were partly informed by the International Plant Protection Convention (Table 10) and National significance criteria (Figure 2). Although the guidelines of the World Organisation for Animal Health were not explicitly considered, the objectives listed in Table 9 are readily applicable to pests and diseases of animals. The Terrestrial Animal Health Code (OIE 2010) provides the following as examples of consequences that could be considered in an import risk analysis:

- Direct consequences
    - animal infection, disease and production losses
    - public health consequences.
- Indirect consequences
    - surveillance and control costs
    - compensation costs
    - potential trade losses
    - adverse consequences to the environment.

Fundamental objectives were also identified through consideration of pre-border and post-border hypothetical pests. Workshop discussions helped to organize the list of objectives and to clear up redundancies and ambiguities in wording. Many commonalities in the pre-border and post-border setting were identified. Some elements that are relevant post-border are irrelevant pre-border due to:

- limitations on which impacts can be considered under international rules in the import risk assessment setting (inability to consider 'fear and worry', 'management capacity building', etc.);
- a more limited set of management actions available in the pre-border setting; and
- the local context of the post-border setting results in a larger set of societal or community concerns that need to be considered.

The pre-border list of fundamental objectives is effectively a subset of the post-border list (Table 9). By encouraging a common set of objectives, Biosecurity Services Group can begin to make improved decisions that are consistent across organisational sub-units and over time, as well as build capacity (data, models and other analytical tools) for assessing consequences efficiently.

A useful tool to help distinguish between means and ends, and to highlight the diverse cause and effect relationships that might condition the achievement of fundamental objectives, is an influence diagram. For example, consider the (hypothetical) results of a pre-border risk analysis for the exotic ant species shown in Table 11. Results are captured in the influence shown at Figure 3. Items at the left of the diagram are triggering events (pest outbreak) or management actions, whereas those at the right are fundamental objectives. The items in the middle are interim effects – things that matter because of their impact on the fundamental objectives and because they help to identify areas where management actions might be helpful. For example, the figure shows that a pest outbreak results in impacts on agricultural plant health, amenity and native plant health. Agricultural plant health impacts affect yield and productivity, and ultimately industry economic losses (the fundamental objective). Plant health can also affect quality, which can affect demand, price and ultimately industry economic losses. Pests directly cause stings, which affect human health. They may also cause damage to infrastructure, resulting ultimately in household economic losses. And so on.

Management actions have consequences of their own, either by affecting the pest outbreak (and thereby changing the nature or magnitude of damages caused by it) or by introducing new consequences. For example a management action that involves spraying a pesticide may have consequences for biodiversity, or it may impose constraints on personal travel or recreational activity. Management actions also introduce costs, which may be borne by government, industry or private households or consumers.

Influence diagrams such as Figure 3 can be used to construct probabilistic models to estimate impacts on fundamental objectives or to structure expert judgments. The influence diagram helps to provide transparency and consistency to such judgments and aids in explaining the rationale behind management actions to stakeholders and decision makers.

As emphasised in section 2.1, the current pre-border risk analysis criteria for consequence results in an assessment that includes both means (e.g., plant health) and ends (e.g., economic losses, impacts on biodiversity). This is a both a logic and a resource allocation problem because it means the same impact is being counted twice (at least).

Table 9. Preliminary table of Fundamental Objectives for biosecurity management. Objectives relevant only for post-border applications are shaded grey. TBD = to be determined.

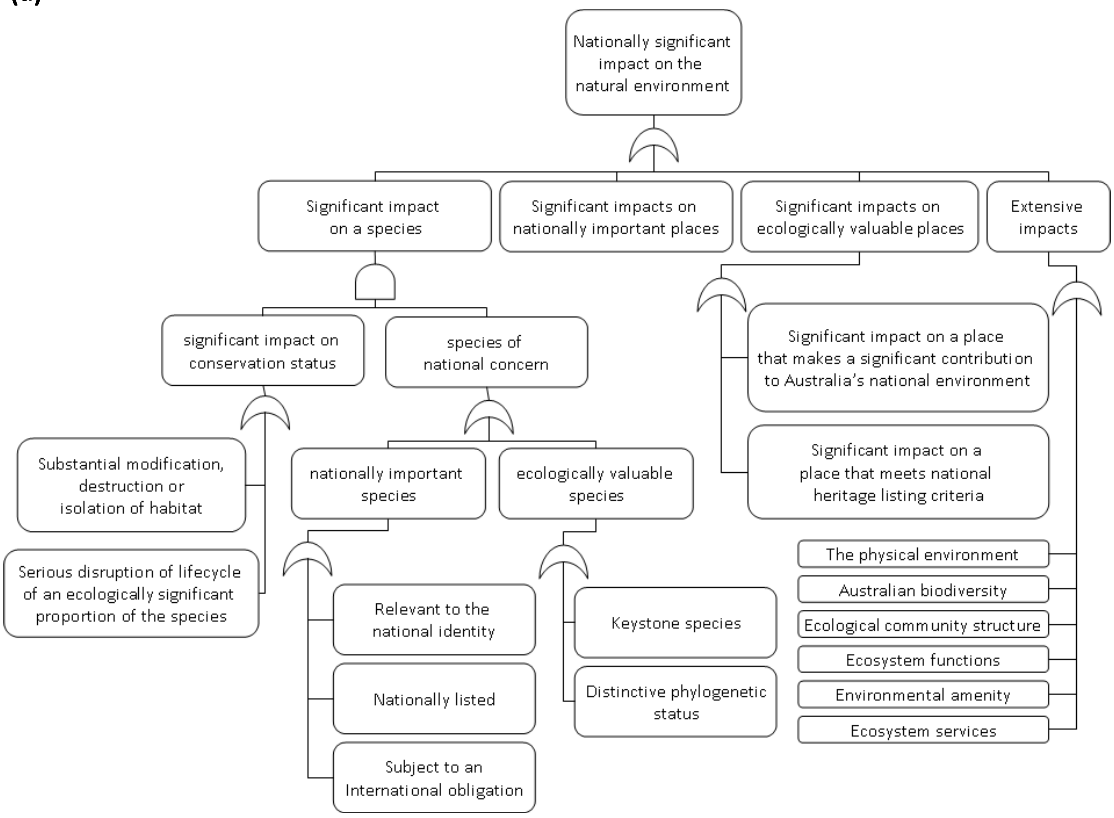
Objectives	Includes	Candidate Attributes
MANAGEMENT COSTS		
Government	Surveillance, eradication, control, research, etc.	$
Business	Surveillance, eradication, control, research, etc.	$
Household / Consumers	Primarily site-level control costs	$
ECONOMY		
Business	Loss of revenue from production loss or market loss	$
Household / Consumers	Loss of property value, cost of repair/replacement	$
ENVIRONMENT		
Ecological Communities	Keystone species, character species	Min population size
Biodiversity	Other species, structural / functional attributes	Min population size
Ecosystem Services	Water and air quality, soil salinity, resistance to fire/flood	Performance or quality indices
HUMAN HEALTH		
Mortality	Attributable deaths	Life years lost
Morbidity	Attributable illness, from discomfort to hospital visits	"equivalent" hospital visits
SOCIETY AND CULTURE		
Community Stability	Includes employment/displacement effects	TBD
Spiritual Values	Places of spiritual importance	TBD
Aesthetics	Landscapes, views, waterways	TBD
Recreation and Culture	Recreational, leisure, cultural activities	Person-days of activity
Personal Loss of Freedom	Impacts on mobility, choices, usually from actions	TBD
Fear and Worry	Perceptions of risk, not necessarily supported by evidence	TBD
MANAGEMENT CAPACITY		
Learning	Benefits to long term capacity to manage pests	TBD

Table 10. Impacts allowed under the World Trade Organisation's International Plant Protection Convention. Note that the uncoloured cells describe consequences arising from the costs of managing the risks posed to managed and unmanaged ecosystems and urban and utility values. Source: Adapted from FAO (2004).

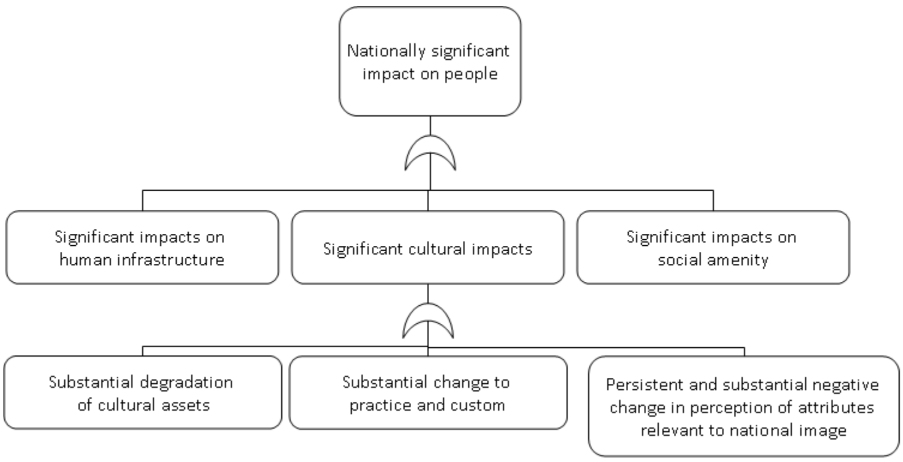
<table>
<tr><th></th><th colspan="3">Consequences of pest entry, establishment and spread on:</th></tr>
<tr><th></th><th>Managed ecosystems</th><th>Unmanaged ecosystems</th><th>Urban and utility</th></tr>
<tr><td rowspan="2">Direct effects</td><td>On primary production flora productivity or sustainability (e.g. yield, quality, mortality and/or morbidity of host).</td><td>On natural environment flora productivity or sustainability (e.g. yield, quality, mortality and/or morbidity of host).
On native keystone endangered or threatened flora or fauna where the keystone species is the direct host</td><td>On amenity landscape flora productivity or sustainability (e.g. yield, quality, mortality and/or morbidity of host).
On human or domesticated animal health (e.g. toxicity, allergies).</td></tr>
<tr><td colspan="3">From incursion management (i.e. feasibility, cost and impacts of containment, eradication and compensation)
On biosecurity risk (e.g. capacity of the pest to act as a vector or pathway for other pests)</td></tr>
<tr><td rowspan="2">Indirect effects</td><td>On domestic or international trade (i.e. transient or permanent restriction or loss of market(s) or new phytosanitary restrictions).
On domestic and international consumer demand (i.e. real or perceived impacts on producer quality traits).
On suppliers of affected primary producers or users of affected outputs (e.g. food processors, canners).
On producer profits that result from changes in production costs, yields or quality. Excludes direct competition.</td><td>On biological or habitat diversity or ecosystem stability (e.g. significant impact on range, composition, displacement or elimination of flora or fauna species).
On native keystone endangered or threatened flora and fauna where the keystone species is not the direct host (i.e. the direct impact on a host has a secondary –indirect – impact on another species).</td><td>On ecological processes (e.g. erosion, water table, potable water, fire hazard or nutrient cycles).
On ecosystem utility (e.g. tourism, recreational or amenity value).
On aesthetic values (e.g. landscape, view or waterway degradation).
On affected communities (e.g. displacement of rural communities, property values or unemployment rate).</td></tr>
<tr><td colspan="3">From the need for additional research and/or advice (e.g. environmental impact and/or pest management studies).
From ongoing new or modified pest management measures (i.e. likely approach, efficacy, cost and potential impacts on ecosystems or existing practices).
From transient or permanent land use restrictions and/or modifications.
From the cost of potential ecosystem/environmental restoration, if feasible.
From secondary or cumulative effects on ecosystems (e.g. need to introduce non-indigenous biocontrol agents to manage the pest).</td></tr>
</table>

Figure 2. Criteria used to designate a pest of national significance under a draft intergovernmental agreement for emergency responses to biosecurity incidents. Criteria are derived, in part, from those outlined in Table 10 under international rules. The structure of the protocol can be summarised using logic trees. To be considered nationally significant, a pest may have impacts on the natural environment (Figure 2(a)) or people (Figure 2(b)) or business (Figure 2(c)). The symbol for an OR gate is and for an AND gate is . Note that human health and primary production impacts are addressed in other cost-sharing agreements, and are therefore not included in these criteria. (Source: adapted from IGA (2009)).

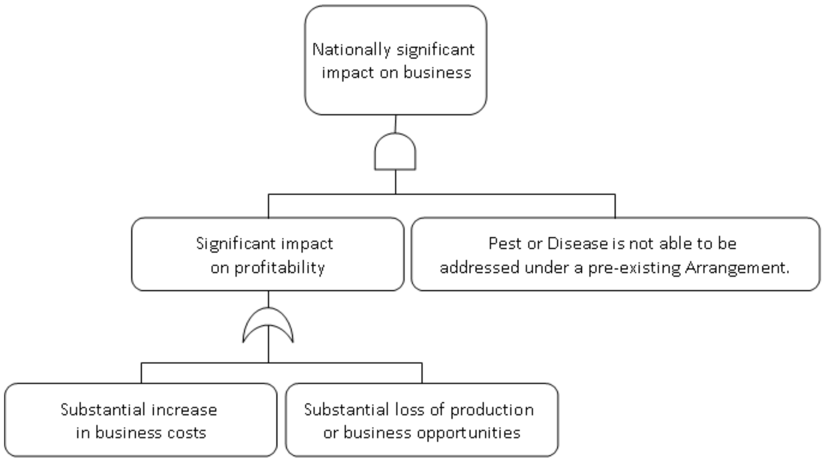
(a)



(b)



(c)



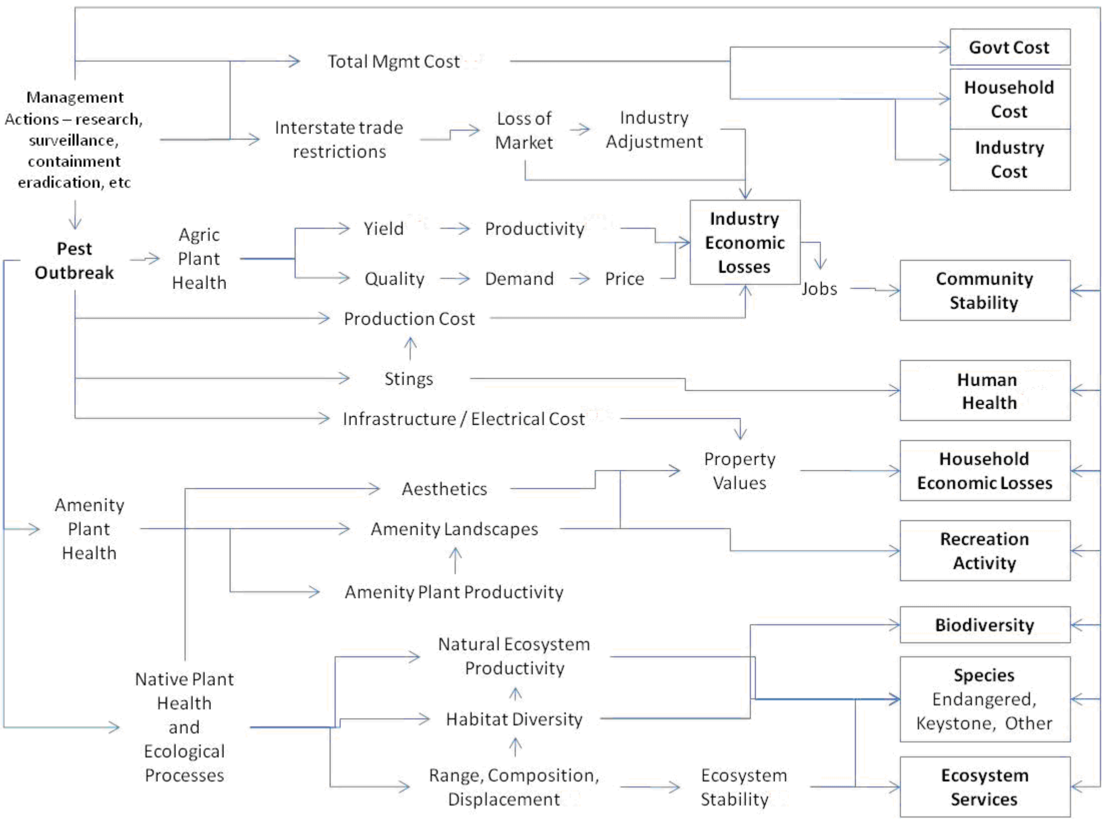


Figure 3. Influence diagram for pre-border risk analysis for an exotic ant species.

Table 11. Assessment of pest impacts under current pre-border risk analysis criteria for a hypothetical exotic ant species.

Criterion	Description of impact
Plant life or health	*Species x* is reported to reduce crop seed set and yield. Extensive seed collection by this species can result in significant loss from sown crops, and result in weed seed importation into cultivated areas, although, it may also reduce weed populations. They can impact biodiversity by reducing seed dispersal of myrmecochorous plants, and their presence in flowers is reported to deter specialist pollinators. This species is reported to girdle citrus tree stems and introduce disease. They may imbibe sap, and damage branches, shoots, buds, flowers and fruits, but this direct damage is usually considered relatively minor and *Species x* is seldom reported to be a direct pest of agricultural crops. *Species x* tend honeydew-producing pests (Homoptera), which may increase their populations on hosts. In Hawaiian pineapple fields these ants are not considered to cause direct damage to pineapple plants, but are considered pests because they tend mealybugs thought to transmit wilt disease.
Other direct aspects of the environment	*Species x* is competitive over other ant species through aggression and cooperative foraging for food. The species is a common urban and rural pest, damaging polyvinyl chloride coatings on electrical wiring and irrigation tubing. The amenity value to humans of *Species x* habitats is reduced because of these ants aggressive stinging behaviour, which can reduce the efficiency of agricultural workers. Severe systemic allergic reactions are rare, but anaphylactic shock resulting from their stings has been reported. Members of the genus to which *Species x* belongs are often at the top of ecosystem dominance hierarchies and may have significant effects on other arthropods.
Eradication and control	Continued regional surveillance for this pest may be required if eradication was considered feasible. Programs to contain, eradicate and/or minimise the impact of this pest are likely to be costly and include pesticide applications. No data is available on the capacity of natural enemies of *Species x* to moderate its impact in Australia.
Domestic trade	The presence of this pest in commercial production areas may result in intra and interstate trade restrictions on a wide range of commodities. These restrictions may lead to loss of markets, especially if containment and/or eradication is proposed, which in turn would likely require industry adjustment.
International trade	This species is an economically important pest within its native range. The presence of this pest in commercial production areas of export commodities may adversely affect access to overseas markets which lack this pest.
Indirect environmental and non-commercial	Presence of *Species x* in agro-ecosystems and natural ecosystems can alter the invertebrate community significantly. It may impact on current pest management strategies. *Species x* is an opportunistic omnivore, and hence both a plant pest and a beneficial predator.

Developing defensible estimates is a challenging task, and without explicit judgments or estimates to provide guidance about the effects of management actions (or an unrestricted scenario) on fundamental objectives, decision makers are left with a nearly impossible task. An evaluation of risks from pest invasions will be more informative, more transparent and more consistent, and ultimately more defensible, to the extent that it reports impacts on the fundamental objectives. Influence diagrams and cognitive maps (see Figures 6 and 8) promote logical clarity and effective communication in the assessment of risks.

Step 3 Develop alternatives

The alternatives are largely shaped by the decision frame. In section 3.1, the alternatives are the pests to which we wish to assign a relative priority. In section 3.2, the alternatives are the candidate management strategies under consideration. In section 3.3, the import risk assessment is obliged to consider the alternative of unrestricted trade (no risk mitigation measures). Where ALOP is not satisfied alternatives involving one or more measures can be considered.

Step 4 Estimate expected consequences

The simple examples provided in Section 1.0 emphasised the importance of estimating *expected* consequence. The example was simplified to consideration of the probability of only two states (invasion or no invasion) and the monetary consequences that arise from those two states.

Biosecurity typically disaggregates 'invasion' into the three successive stages of entry, establishment and spread. A common (and misplaced) convention is to consider only those consequences that arise at the point of entry, establishment and spread (EES). But consequences might arise at any point along the continuum, depending on what is included in the characterisation of consequence. For example, the World Trade Organisation considers the costs of risk management to be a legitimate component of consequence in a pest risk assessment (Table 10). Figure 4 urges consideration of the possibility of consequences arising prior to entry (E'), at the point of entry only (EE'; i.e. entry but no subsequent establishment), or entry and establishment but no spread (EES'). Failure to recognise consequences prior to EES will result in systematic underestimation of expected consequence.

For each alternative, expected consequences need to be estimated against each fundamental objective. Estimates need to consider each pathway in Figure 4. In decision frames that include the costs of risk management, those costs likewise need to be cast in terms of expected costs arising at each point along the biosecurity continuum (see Figure 10).

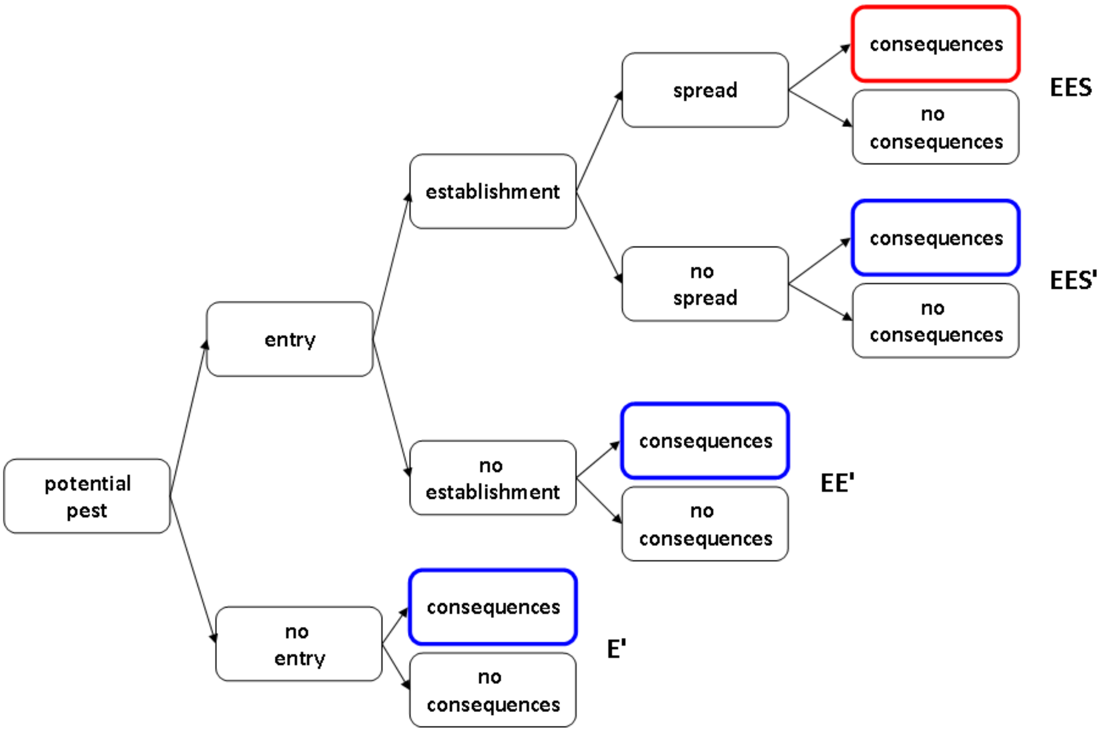


Figure 4. Event tree for potential consequences along the biosecurity continuum. There are four states that collectively represent the complete set of circumstances from which adverse consequences can potentially arise: E' - no entry, EE' - entry, but no establishment, EES' - entry, establishment, but no spread, and EES - entry, establishment and spread. Risk assessment protocols commonly consider consequences at the point of entry, establishment and spread (red box). A more complete characterisation of expected consequence would consider the possibility of impacts at the point of entry or establishment (blue boxes).

Step 5 Evaluate trade-offs

This step requires articulation of societal preferences or those of the decision-maker(s) acting on behalf of society (i.e. impacts to be preferentially avoided in the real world setting of a finite operating budget for biosecurity). Aggregating consequences across monetary and non-monetary values (represented by fundamental objectives) requires trade-offs. More specifically, we need to weigh the expected consequences for business against those for amenity values and environmental values. Weights can be elicited using a variety of techniques (Hajkowicz et al. 2000), not all of which are credible. The weight assigned to any single fundamental objective is a function of two elements; (a) the inherent importance of the objective, and (b) the range of the consequences estimated across all alternatives. A very common mistake in assigning weights is to ignore the range of consequences (Keeney 2002, Steele et al. 2009).

Here we advocate 'swing' weights, a technique that makes the range of expected consequences salient to decision-makers (Fischer 1995). The technique requires an initial estimate of the best and worst possible *expected* consequences of invasion of any pest. The 'best' consequences are totally benign impacts. Let's say 'worst' estimates are those in Table 12. Now imagine a pest that is worst on every objective. Let's call this pest *Misery pox*. It is expected to cost business $20 billion, have an extreme impact on amenity, and directly threaten 2,000 Australian native species.

The first of two tasks in swing weighting is to assign a rank to the objectives by considering the range of outcomes. If you could 'swing' the outcome of only one objective from its worst to best, which would it be? That is, would you prefer a decrease in business costs from $20 billion to zero? Or zero amenity impacts? Or zero environmental impacts? Let's say we choose environmental impacts. We assign it the number 1 ranking, which implies that the range in impact from 2,000 susceptible species to zero matters more than a $20 billion cost to business or a full 100 point difference on our amenity scale. Next we get the option to swing a second objective from worst to best. Let's say that we choose business impacts, so it is assigned a ranking of two, and amenity a ranking of 3.

The second task is to quantify the rank-ordered judgments. Begin by assigning a weight of 100 to the objective with the most important range (environmental impact in our example). To assign a quantitative weight to the second ranked objective (business), focus on the range of outcomes. The aim is to judge the importance of the range of business impacts relative to the range of environmental impacts. For example, if you judge the range of outcomes for business impacts is 4/5 as important as that for the environment, then a weight of 80 would be given to business. Finally the range of amenity impacts is considered alongside the range of environmental impacts. In our example, we've judged the range in amenity to be half as important (50) as the range in environmental impacts. Following quantification the weights are normalised to sum to one (Table 12).

These weights are the arbitrary invention of the authors of this report. They are not defensible from a social or organisational perspective. But swing weights (or alternative credible methods) could be used to elicit the preferences of a sample of decision-makers and stakeholders.

If weights are derived using the best and worst possible scenarios for impacts against each objective they are called *global* weights. The weights in Table 12 are global. We'll use these weights for *local* characterisation of the expected consequences of individual (hypothetical) pest species. Use of global weights in this way assumes linear trade-offs across the full range of outcomes for each pair of objectives (Fischer 1995; see Appendix).

Table 12. Swing weights for the three fundamental objectives.

Objective	Best	Worst	Rank	Weight	Normalised weight
Minimise business impacts	0	$20 000 M	2	80	80/230 = 0.35
Minimise amenity impacts	0	100	3	50	50/230 = 0.22
Minimise environmental impacts	0	2,000 species	1	100	100/230 = 0.43
				Sum = 230	Sum = 1.00

3.1 Prioritising pests

Characterising the consequences of the vast number of alien taxa that may invade is overwhelming. The maintenance of priority pest lists serves as a screening tool. It will be effective in guiding management where the distribution of expected consequences is highly skewed (Figure 5), where pest lists successfully capture species in the tail, and where the risk mitigation effects of management actions directed at priority species are also effective against the mass of other (non-priority) pest species.

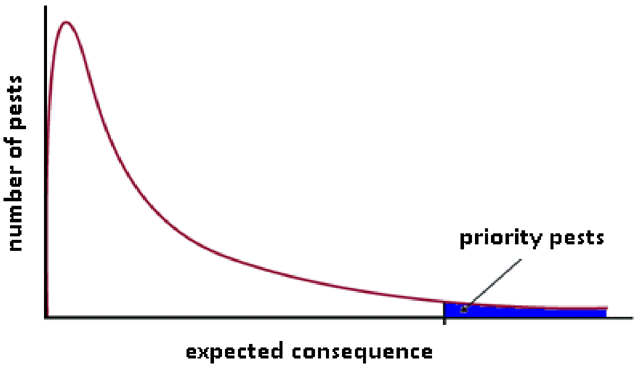


Figure 5. Hypothetical distribution of adverse consequences of pests. Most pests have small expected consequences. Priority pest lists seek to identify those species associated with the tail of the distribution.

For illustrative purposes let's say we have only three ***alternative*** pest species *x, y* and *z* we need to place in rank (priority) order with respect to their expected consequences. That is the ***decision frame*** is to prioritise pests in terms of their expected adverse consequences in the absence of any management action. Let's assume all three pests *x*, *y* and *z* are currently exotic to Australia. The fundamental ***objectives*** are to minimise adverse business impacts, amenity impacts, and environmental impacts. Priority pests are those that pose the greatest risk to our objectives. The ***trade-offs*** in those objectives were approximated in the elicitation of swing weights described above. The value judgments underpinning trade-offs need to be combined logically with our ***estimates of expected consequence***.

To estimate *expected* consequences (Step 4 of the framework) we need a model that captures our understanding of cause and effect. Models help insulate against logical inconsistencies in estimation. They may be simple and qualitative (e.g. conceptual models, cognitive maps or influence diagrams) or they may be quantitative and, in relative terms, technically demanding (e.g. Bayes nets or Monte Carlo simulations). Here we use a cognitive map to capture our understanding of cause-and-effect. Figure 6 shows how species *x* (a fungal pathogen) may enter Australia and establish, spread and ultimately have adverse impacts on our fundamental biosecurity objectives. Cognitive maps would also need to be prepared for species *y* and *z*.

Cognitive maps are graphical representations in which key concepts are nodes and causal relationships are the arcs between them. They are an extension of conceptual models. Elicitation involves selecting relevant concepts, and specifying the direction and sign (positive or negative) of the causal associations between nodes (Hodgkinson et al. 2004). Bayes nets are an alternative means of capturing expert opinion. In relative terms, cognitive maps involve a modest elicitation burden on experts at the cost of lesser inferential clarity. Our preference for cognitive maps is motivated by recognition that elicitation burden is the primary constraint to broader use of expert judgment (Hoffman and Lintern 2006). Biosecurity problems that demand greater clarity may warrant use of more demanding approaches to modelling.

Typically, data to inform estimates of expected consequence are sparse or entirely absent, making expert judgment the only alternative. Use of cognitive maps with four-point elicitation (Speirs-Bridge et al. 2010) can buffer against overconfidence commonly encountered in expert judgment (Yaniv 2004). Here we initially use best estimates to describe the elements of likelihood and consequence that comprise judgments of expected consequence against each fundamental objective. Later in section 3.2 we illustrate a method for treating uncertainty in estimates and emphasise its relevance to decision-makers who are not risk-neutral.

Many pests may be highly destructive should they successfully invade. But estimates of consequence that ignore the probability of those consequences being realised are prey to alarmism and misallocation of resources. Point estimates of the consequences for the three hypothetical pests *x*, *y* and *z*, are shown in Table 13, ignoring the likelihood of entry, establishment and spread. That is, estimates implicitly assume all pests have a probability of 1.00 of entering, establishing and spreading. This naïve characterisation of consequence would assign highest priority to Pest *x*.

Table 13. Consequences of three hypothetical pests, ignoring likelihood of entry, establishment or spread.

	Business ($M)	Amenity (constructed scale)	Environment (number of directly susceptible native species)
Pest *x*	$10,020	70	8,000
Pest *y*	$0.0083	10	590
Pest *z*	$11.6	10	90

Estimates of *expected* consequences involve consideration of the likelihood of entry, establishment and spread. Estimates of the probabilities of these events for species *x, y* and *z* are shown in Table 14*,* from which estimates of the probability of each of the four states of the biosecurity continuum can be calculated. For example, for species *x*,

Pr{E'} = 1 - Pr{entry} = 1 – 0.1 = 0.9.
Pr{EE'} = Pr{entry} × (1 - Pr{establishment}) = 0.10 × (1 – 0.05) = 0.095.
Pr{EES'} = Pr{entry} × Pr{establishment} × (1 - Pr{spread}) = 0.10 × 0.05 × (1 – 0.02) = 0.0049.
Pr{EES} = Pr{entry} × Pr{establishment} × Pr{spread}) = 0.10 × 0.05 × 0.02 = 0.0001.

Failure to consider each of these four states leads to poor estimation of likelihood in the prediction of expected consequences (limitation #3 identified in Section 2.2 of this report). Note that the four states are mutually exclusive and that the probability of observing the four states for any single species sum to one.

Figure 7 uses this information to probabilistically describe the pathways that may result in adverse consequences for species *x*. The cognitive map (Figure 6) shows no consequences prior to establishment (i.e. impacts are assumed to be non-existent or trivial). It does however communicate the judgment that for species *x* the impacts on business via market loss will be non-negligible at the point of establishment, irrespective of whether or not the pest subsequently spreads. So the two states EES' and EES are relevant.

In sections 3.2 and 3.3 we show how all four states are relevant to decision-making involving candidate alternatives for management intervention, because among the alternatives may be risk mitigation measures that are deployed pre-entry, pre-establishment or pre-spread.

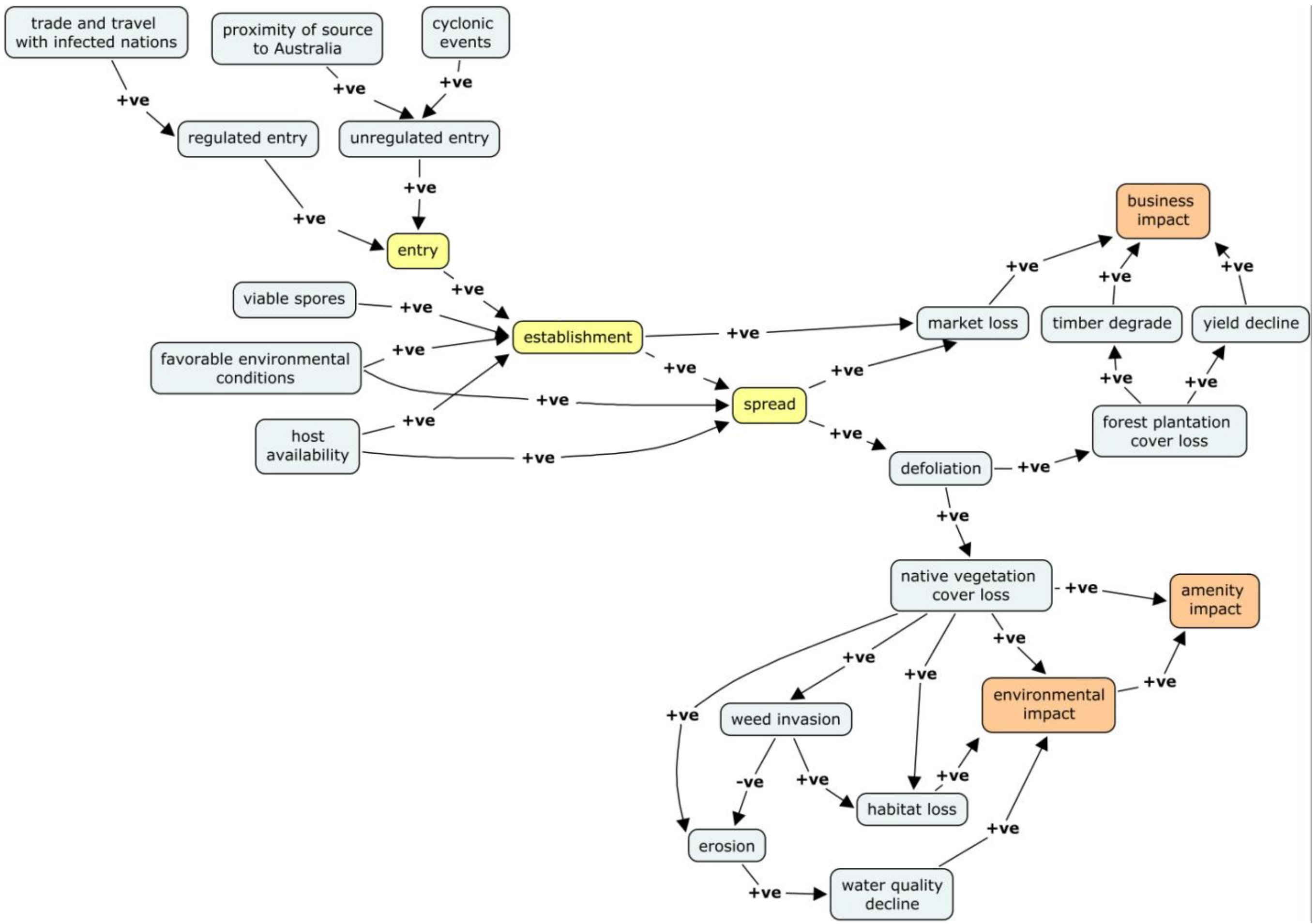


Figure 6. Cognitive map showing our understanding of the main causal elements leading to consequences from a hypothetical pest species, a fungus capable of extensive defoliation of eucalypts. Consequences (red nodes) correspond with fundamental objectives. The expected magnitude of consequences is conditioned by the probability of entry, establishment and spread (yellow nodes). Note that the cognitive map anticipates business impacts at the point of pest establishment via market loss. All other impacts are assumed to be negligible until the pest has spread.

Table 14. (a). Hypothetical expert judgments of the probability of entry, establishment and spread for species *x*, *y* and *z*. These judgments can be used to calculate **(b)** the probability of observing each of four states along the biosecurity continuum.

(a)

Event	Probability		
	x	*y*	*z*
entry	0.10	0.80	0.60
establishment|entry	0.05	0.50	0.70
spread|est	0.02	0.90	0.95

(b)

State	Probability		
	x	*y*	*z*
E'	0.9000	0.2000	0.4000
EE'	0.0950	0.4000	0.1800
EES'	0.0049	0.0400	0.0210
EES	0.0001	0.3600	0.3990

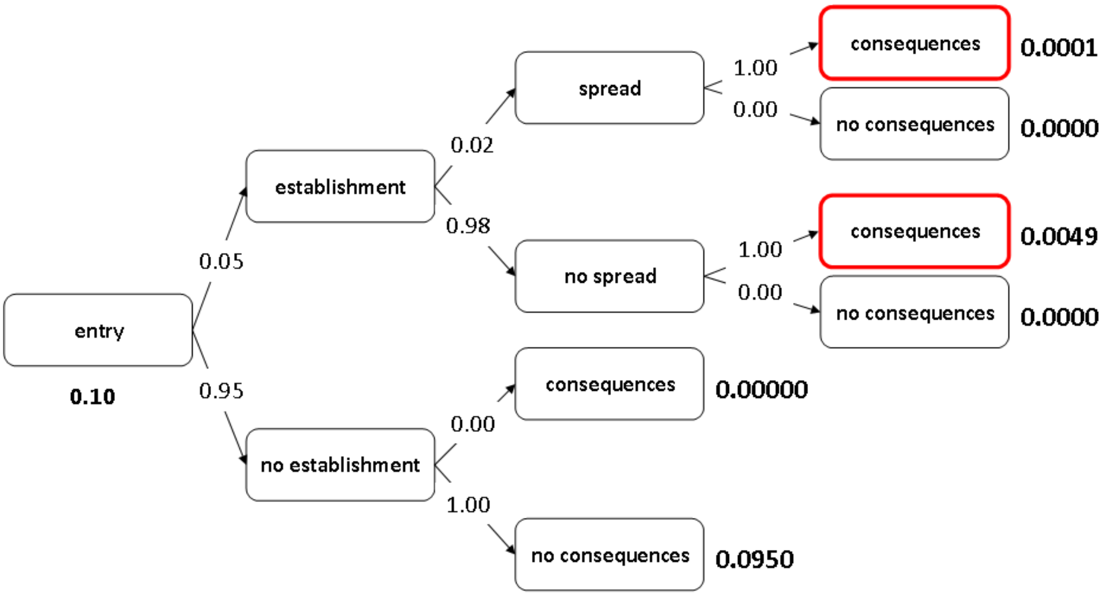


Figure 7. Probabilistic event tree for entry, establishment and spread of the hypothetical Pest *x*. Pathways involving non-negligible consequences are highlighted red.

Details of judgments for likelihood and consequence for species *x* across the four states are shown in Table 15. *Summed expected consequence* for each fundamental objective is the sum of the products of likelihood and consequence estimated for each state. For Pest *x* the expected consequences are a $1.098 M cost to business, an amenity impact of 0.0070 and an environmental impact of less than one (0.8) directly susceptible native species.

Corresponding judgments made for species *y* and *z* provide the expected consequences shown in Table 16. Pests could be prioritised without formal weighting on the basis of the information presented in Table 16. But unlike Table 1, no single pest dominates across all objectives (although pest *z* is clearly expected to be a greater threat than pest *x*). Value judgments involving trade-offs need to be made.

Table 15. Best estimate judgments for likelihood and consequence for Pest *x*. Consequences for business are described in $M, for amenity on a scale from 0 – 100, and for environment the number of directly susceptible native species.

State	Likelihood	Consequences		Expected consequence
E'	0.9000		Nil	Nil
EE'	0.0950		Nil	Nil
EES'	0.0049	Business	20	0.0980
		Amenity	0	0
		Environment	0	0
EES	0.0001	Business	10,000	1.0000
		Amenity	70	0.0070
		Environment	8,000	0.8000
			Business sum	1.0980
			Amenity sum	0.0070
			Environment sum	0.8000

Table 16. Summed expected consequences for species *x*, *y* and *z*.

	Business ($M)	Amenity (constructed scale)	Environment (number of directly susceptible native species
Pest *x*	$1.098M	0.0070	0.8
Pest *y*	$0.003M	3.5000	212
Pest *z*	$4.624M	4.0770	36

In Table 17, we use the weights obtained from the swing weighting exercise to obtain a *standardised expected consequence score* through simple weighted summation. This score can be coarsely interpreted as the proportional impact of a pest species relative to a score of 100 for the extreme (and fictitious) *Misery pox*. Before applying the weights, summed expected consequences are rescaled from 0 to 100 according to the global range of consequences used to elicit weights (Table 12; Fischer 1995). That is, the rescaled summed expected consequence (rSEC) for pest *i* on objective *j*,

$$rSEC_{ij} = [(SEC_{ij} – best_{gj})/(worst_{gj} – best_{gj})] \times 100,$$

where $best_{gj}$ and $worst_{gj}$ are the best and worst outcomes in the global range on objective *i*. For example, the rescaling of the $1.098M expected impact on business associated with species *x* is rescaled as [(1.098 – 0)/(20,000 – 0)] × 100 = 0.00549.

The results show that the highest priority species in terms of expected adverse consequence in the absence of any management action is species *y* (standardised expected consequence score = 5.3263), then species *z* (1.679) and then species *x* (0.0207). Note that species *x* is the lowest priority of the three species, in contrast to naïve interpretation of consequences described in Table 13. The likelihood of observing relevant states (Table 14) is needed to derive *expected* consequences.

Table 17. Standardised expected consequence for species *x*, *y* and *z*.

	Summed expected consequence (original units)			Rescaled summed expected consequence			Standardised expected consequence
Pest	Business	Amenity	Environment	Business	Amenity	Environment	
x	1.098	0.007	0.8	0.00549	0.00700	0.04000	0.0207
y	0.003	3.492	212	0.00001	3.49200	10.60020	5.3263
z	4.624	4.077	36	0.02312	4.07700	1.80001	1.6790
			weight	0.35	0.22	0.43	Sum = 7.0260

3.2 Assessing the merit of alternative actions according to their efficiency

There is a tendency among management agencies to generate priority lists and then work down the list to develop species-specific programs until the budget is exhausted. This is unlikely to be an efficient approach. Priority species lists are not designed to directly inform management action (Possingham et al. 2002). They do not consider what management actions are available to mitigate the threat posed by pest(s), their technical and social feasibility, or their cost (Pannell et al. 2009).

Management agencies are more directly concerned with the merit of management actions rather than the threat posed by pest species. That is, the more immediately relevant alternatives under consideration by managers are not pests, but rather actions. The decision to invest in any action should rest on considered appraisal of the *returns* expected on the investment with respect to *risks* posed to fundamental objectives. One approach to characterising the merit of a management action (or suite of management actions packaged into a strategy) according to this principle of risk return is its cost efficiency. Here we develop a metric of cost efficiency that builds on the scientific and social judgments used to prioritise pest species in the previous section.

Let's denote the standardised expected consequence score in the absence of management action, C_0 (i.e. standardised expected consequences *C* where action = 0). Summing C_0 over the three species x, y and z, we obtain 0.0207 + 5.3263 + 1.6790 = 7.0260. That is, in the absence of any management action we expect an impact from all three species equivalent to about 7% that of *Misery pox*.

The efficiency *E* of strategy *i* can be calculated as (Joseph et al. 2009),

$$E_i = \frac{\sum (C_0 - C_i) \times S_i}{\$_i},$$

where $\sum(C_0 - C_i)$ is the difference between standardised expected consequences in the absence and presence of strategy *i* summed over all pest species considered; $\$_i$ is the cost of implementing the strategy; and S_i is the probability of successfully implementing the strategy. S_i can include consideration of technical, social and political feasibility. S_i can be incorporated in estimates of C_i derived using four-point elicitation (Speirs-Bridge et al. 2010), so long as factors affecting implementation success are made plain to those making judgments through use of cognitive maps or other aids. In this case, the metric of efficiency reduces to

$$E_i = \frac{\sum (C_0 - C_i)}{\$_i}.$$

Note that there is an implied trade-off with the costs of implementation ($\$_i$). The risk-return metric E_i does not seek to explicitly trade-off these costs against fundamental objectives. Rather, the metric describes the standardised reduction in expected adverse consequences per unit expenditure under any strategy *i*.

Candidate management strategies will typically comprise investment in one or more discrete actions at one or more discrete points along the biosecurity continuum. The specification of investment in actions pre-entry, pre-establishment, pre-spread and post-spread is important because it affects *expected* implementation costs ($\$_i$). Let's say we have the following generic actions to choose from in the formulation of candidate strategies.

Pre-entry actions
Offshore Surveillance and intelligence
Offshore eradication and control strategies
Regulate trade - certified treatments or disease free areas
Border surveillance
Active surveillance in Australia
Enhanced passive surveillance

Pre-establishment actions
Active surveillance in Australia
Enhanced passive surveillance

Pre-spread actions
Active surveillance in Australia
Enhanced passive surveillance
Delimit and eradicate
Delimit and control

Post-spread actions: contain spread
Active surveillance
Enhanced passive surveillance
Delimit and eradicate
Delimit and control

Post spread actions: Manage impacts
Host replacement
Change agronomic systems
Noah's ark

We note that management actions can also include investment in research, including

- Offshore Research and Development
- Ecological research
- Diagnostics
- Improving surveillance techniques
- Improving control techniques
- Improving host/ecosystem resistance

We ignore these actions in the illustrative example presented here.

Figure 8 includes actions in the cognitive map for Pest *x*. Identifying candidate strategies is a substantial task in itself. The capacity of individual actions to reduce expected consequences through reduction in the probability of entry, establishment or spread, or the mitigation of impacts post-spread is difficult to assess. Again, cognitive maps assist clear thinking about the relative effectiveness of individual actions and sensible packaging of actions into strategies. Strategy tables are designed specifically for formulation of sound alternatives (Goodwin and Wright 2001). Considerable time and effort is needed to identify *prima facie* sound candidate alternative management strategies. The inclusion of cost-prohibitive or ineffective alternatives will add substantially to the elicitation burden for no return.

Now let's say that after some consideration the strategies outlined in Table 18 (together with cost estimates) are identified as alternatives worth detailed consideration. Strategy *a* involves moderate investment across a range of pre-entry, pre-establishment and pre-spread actions. No funds are reserved for containing the spread or managing impacts. Imagine that the highest priority pest identified in section 3.1 (species *y*) is very difficult to detect pre-entry, and difficult to control or manage post-spread. Strategy *b* is largely motivated by this high priority species. It avoids the costs of up-front pre-entry actions, but should an incursion occur then large sums are invested pre-establishment and pre-spread. Again, no funds are reserved for containing the spread or managing impacts. Strategy *c* hedges its investments across the full suite of actions along the biosecurity continuum. The 'do nothing' scenario is not strictly one of no action. It assumes a minimal maintenance cost in border surveillance.

The steps in estimating C_0 for each pest species under the do nothing scenario were outlined in section 3.1 above, with results reported in Table 17. For each candidate strategy *i* the standardised expected consequences C_i need to be similarly obtained. The management actions of each strategy will affect the probability of entry, establishment and spread differently. Post-spread actions that seek to manage impacts will reduce those impacts relative to the do nothing scenario. Let's say use of expert judgment on these matters provides the best estimates shown in Table 19 and Figure 9. Without considering the costs of implementation the most effective strategy is *b*, the one designed to counter the high impact pest species *y*, with standardised expected consequences summed over the three species of 4.46. Expert judgment anticipates positive correlation in the response of the three pest species to each strategy (Figure 9), implying efficiencies in the consideration of multiple species when considering biosecurity strategies. The strongest correlation is between species *x* and *z*. The response of species *y* is more muted.

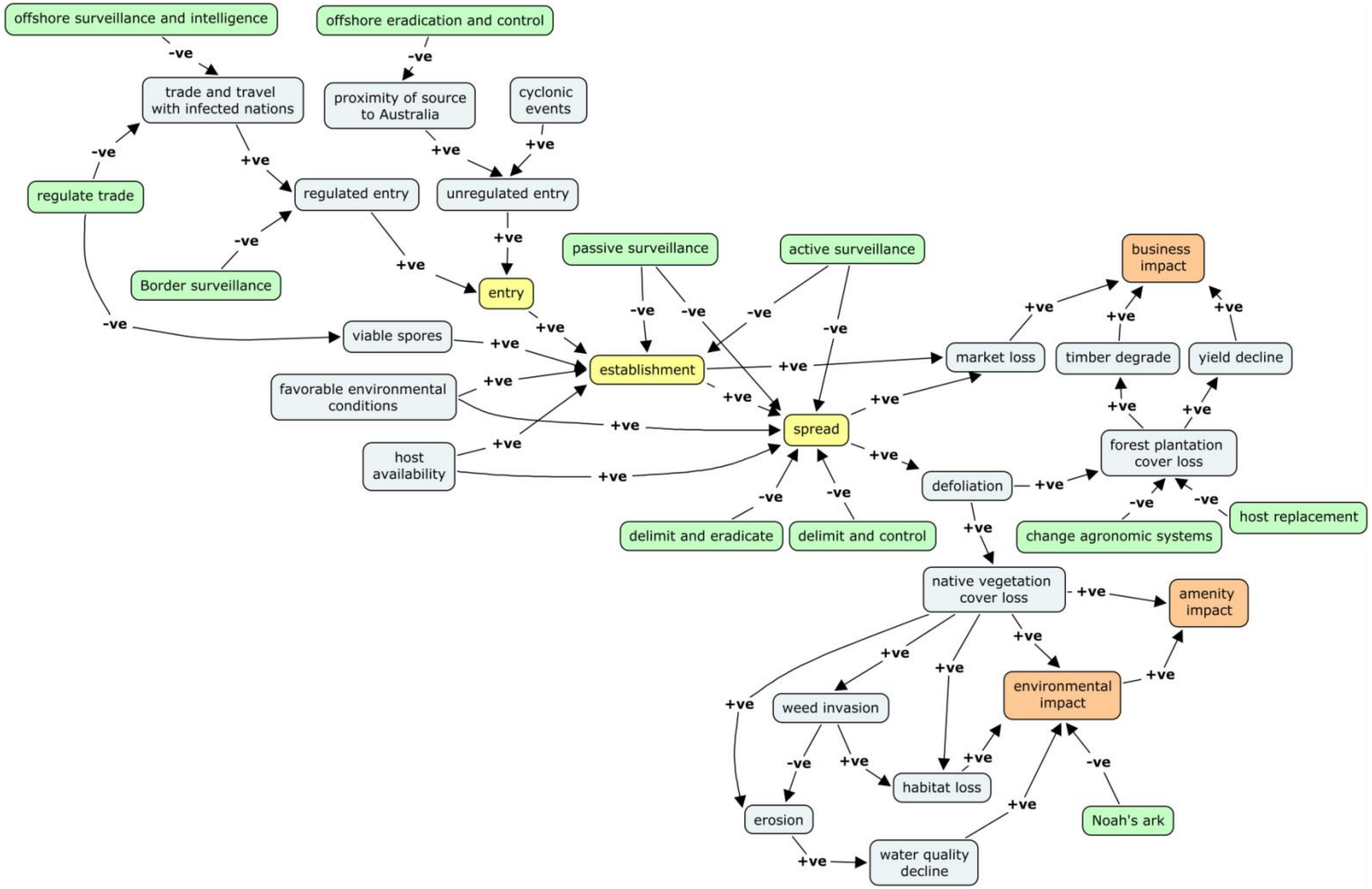


Figure 8. Cognitive map showing candidate management actions for mitigating the expected consequences of invasion of a hypothetical pest. The challenge for biosecurity is identification of a suite of actions that will reduce expected consequences most efficiently.

Table 18. Alternative strategies and levels of investment in constituent actions. Strategies refer to risk mitigation across multiple species. Note that the expenditure beyond pre-entry actions is conditional on pest entry, establishment and spread.

	$M Do nothing	$M Strategy *a*	$M Strategy *b*	$M Strategy *c*
Pre-entry actions				
Offshore Surveillance and intelligence		$4.0		$2.0
Offshore eradication and control strategies		$5.0		$2.5
Regulate trade		$2.0		$1.0
Border surveillance	$1.0	$7.0	$1.0	$3.5
Active surveillance in Australia		$5.0		$2.5
Enhanced passive surveillance				$2.5
Pre-establishment actions				
Active surveillance in Australia		$20.0	$100.0	$10.0
Enhanced passive surveillance		$5.0	$25.0	$2.5
Pre-spread actions				
Active surveillance in Australia		$20.0	$100.0	$10.0
Enhanced passive surveillance		$5.0	$25.0	$2.5
Delimit and eradicate		$25.0	$125.0	$12.5
Delimit and control		$25.0	$125.0	$12.5
Post-spread actions: contain spread				
Active surveillance				$5.0
Enhanced passive surveillance				$2.5
Delimit and eradicate				$12.5
Delimit and control				$12.5
Post-spread actions: Manage impacts				
Host replacement				$20.0
Change agronomic systems				$20.0
Noah's ark				$20.0

Now we need to estimate the expected cost of implementation ($\$_i$). The cost of each strategy depends on the probability of each of the four states of the biosecurity continuum and the point at which various actions comprising a strategy are triggered along the continuum. Table 20 shows the relevance of each state to pre-entry, pre-establishment, pre-spread and post-spread actions. Table 21 shows expert judgments on the probability of each of the four mutually exclusive states under each risk management scenario. Note that although species *y* was the highest priority species, the relatively invariant probabilities reported in Table 21 across the four scenarios reflects the view that there are no actions available to deal effectively with the threat. Recall that the states are mutually exclusive, so we can simply sum the probability of relevant states for each species to calculate the probability of actions being triggered for any single scenario.

Table 19. Standardised expected consequence for species *x*, *y* and *z* under each of three alternative risk management strategies.

(a) Strategy a

	Summed expected consequence (original units)			Rescaled summed expected consequence			Standardised expected consequence
Pest	Business	Amenity	Environment	Business	Amenity	Environment	
x	0.180	0.001	0.1	0.00090	0.00105	0.00600	0.0031
y	0.003	3.051	185.2	0.00001	3.05061	9.26033	4.6531
z	0.956	0.843	7.4	0.00478	0.84299	0.37218	0.3472
			weight	0.35	0.22	0.43	Sum = 5.0034

(b) Strategy b

	Summed expected consequence (original units)			Rescaled summed expected consequence			Standardised expected consequence
Pest	Business	Amenity	Environment	Business	Amenity	Environment	
x	0.070	0.000	0.0	0.00035	0.00035	0.00200	0.0011
y	0.002	2.794	169.6	0.00001	2.79360	8.48016	4.2611
z	0.556	0.490	4.3	0.00278	0.49046	0.21654	0.2020
			weight	0.35	0.22	0.43	Sum = 4.4641

(c) Strategy c

	Summed expected consequence (original units)			Rescaled summed expected consequence			Standardised expected consequence
Pest	Business	Amenity	Environment	Business	Amenity	Environment	
x	0.265	0.001	0.2	0.00133	0.00147	0.00840	0.0044
y	0.003	3.004	182.4	0.00001	3.00390	9.11853	4.5818
z	1.017	0.897	7.9	0.00508	0.89663	0.39587	0.3693
			weight	0.35	0.22	0.43	Sum = 4.9555

For example, for species *x* the probability that pre-spread actions will be triggered under strategy *b* is

Pr{EES'} + Pr{EES} = 0.001 + 0.000 = 0.001.

The corresponding probability for species *y* is 0.072 + 0.288 = 0.360, and for species *z* is 0.072 + 0.048 = 0.120.

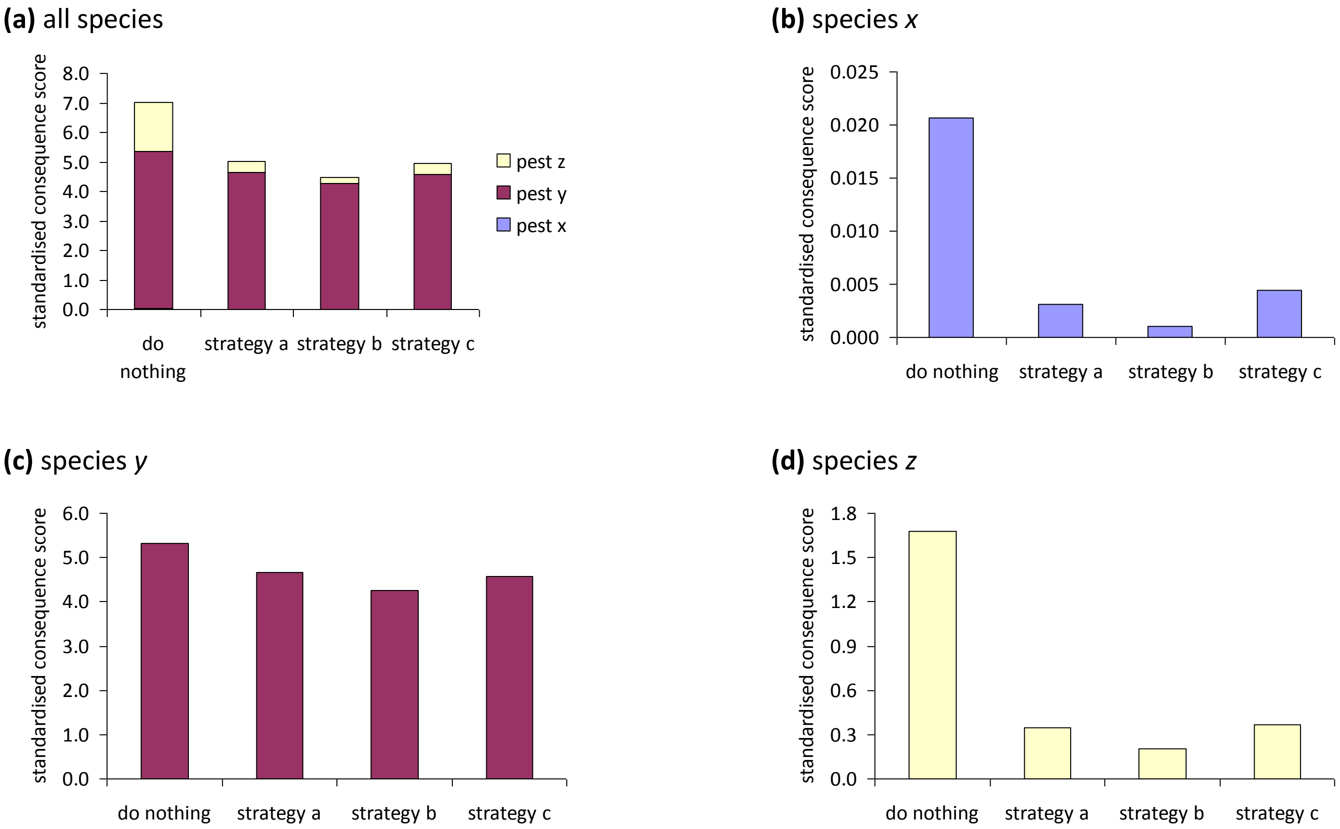


Figure 9. Standardised expected consequences under each scenario for (a) all species, (b) species *x*, (c) species *y* and (d) species *z*.

Table 20. Points along the biosecurity continuum where risk management actions are triggered.

State	Point of implementation of actions along the biosecurity continuum			
	pre-entry	pre-est	pre-spread	post-spread
E'	×			
EE'	×	×		
EES'	×	×	×	
EES	×	×	×	×

Table 21. Probability of each of the four states of the biosecurity continuum under each strategy.

Scenario	Event	Pest *x*	Pest *y*	Pest *z*
Do nothing	E'	0.9000	0.2000	0.4000
	EE'	0.0950	0.4000	0.1800
	EES'	0.0049	0.0400	0.0210
	EES	0.0001	0.3600	0.3990
Strategy a	E'	0.9500	0.2200	0.7000
	EE'	0.0485	0.4056	0.1500
	EES'	0.0015	0.0599	0.0675
	EES	0.0000	0.3145	0.0825
Strategy b	E'	0.9000	0.2000	0.4000
	EE'	0.0990	0.4400	0.4800
	EES'	0.0010	0.0720	0.0720
	EES	0.0000	0.2880	0.0480
Strategy c	E'	0.9300	0.2100	0.5500
	EE'	0.0672	0.4029	0.1800
	EES'	0.0028	0.0465	0.0945
	EES	0.0000	0.3406	0.1755

Now for the sake of simplicity let's say the investments in actions under each strategy described in Table 18 are triggered if any one of the three pest species reaches the corresponding point of invasion along the biosecurity continuum. For example, pre-spread actions will be triggered if species *x* or species *y* or species *z* become established. Assuming the three species' invasion pathways are independent, the probability of spending the $375M earmarked for pre-spread actions under strategy *b* (Table 18) is,

$\Pr\{x \cup y \cup z\}$

$= \Pr\{x\} + \Pr\{y\} + \Pr\{z\} - \Pr\{x \cap y\} - \Pr\{x \cap z\} - \Pr\{y \cap z\} + \Pr\{x \cap y \cap z\}$

$= 0.001 + 0.360 + 0.120 - (0.001 \times 0.360) - (0.001 \times 0.120) - (0.360 \times 0.120) + (0.001 \times 0.360 \times 0.120)$

$= 0.437.$

Results of calculations for each strategy and each set of actions along the continuum are shown in Figure 10. Of the three alternatives for active risk management, the greatest expected cost is strategy *b* at $281.01M. The expected cost of strategy *a* is $79.52M and for strategy *c*, \$88.14M. Subtracting the \$1.00M cost of the do nothing scenario gives the following estimates for $\$_i$,

Strategy *a* = \$ 78.52M
Strategy *b* = \$280.01M
Strategy *c* = \$ 87.14M.

Figure 10. Expected costs of each strategy.

	pre-entry		pre-establishment		pre-spread		post-spread		expected cost
do nothing	1.000 × \$1M	+	0.928 × zero	+	0.654 × zero	+	0.615 × zero	=	\$ 1.00 M
strategy a	1.000 × \$23M	+	0.854 × \$25M	+	0.469 × \$75M	+	0.371 × zero	=	\$ 79.52 M
strategy b	1.000 × \$1M	+	0.928 × \$125M	+	0.437 × \$375M	+	0.322 × zero	=	\$ 281.01 M
strategy c	1.000 × \$14M	+	0.893 × \$12.5M	+	0.554 × \$37.5M	+	0.456 × \$92.5	=	\$ 88.14 M

We now have all the elements needed to describe the efficiency of each strategy.

- Expected consequences in the absence of management action (C_o; Table 17)
- Expected consequences for each management strategy *i* (C_i; Table 19)
- Expected costs of each candidate management strategy *i* ($\$_i$; above).

The efficiency of each strategy is,

$$E_a = \frac{7.0260 - 5.0034}{78.52} = 0.026,$$

$$E_b = \frac{7.0260 - 4.4641}{280.01} = 0.009,$$

$$E_c = \frac{7.0260 - 4.9555}{87.14} = 0.024.$$

Strategy *a* is the best strategy according to the efficiency metric. It is marginally better than strategy *c*. After including expected costs, the worst strategy is *b*. The metric is a descriptor of the return on risk per unit expenditure. More specifically, the efficiency of strategy *a* is an expected reduction in adverse impacts equivalent to 0.026% of the extreme impacts of *Misery pox* per million dollars spent.

Uncertainty

The methods presented above have used only best estimates. Expert judgment and formal models of cause-and-effect are uncertain. In four point elicitation, best estimates are accompanied by plausible bounds describing the uncertainty in expert judgments of quantities (Speirs-Bridge et al. 2010). These uncertainties can be incorporated into calculations for the efficiency metric using interval arithmetic (Morgan and Henrion 1990).

For example, let's say we have only two pest species, A and B and a single strategy *i* for which we wish to calculate E_i. After aggregating the judgments of several experts we have the following plausible bounds for standardised expected consequence:

	C_0	C_i
Pest A	[0.2, 0.4]	[0.1, 0.3]
Pest B	[0.5, 0.8]	[0.4, 0.5]

Interval arithmetic treats uncertainty conservatively. It reports the widest bounds possible from uncertain inputs.

Recall that $E_i = \frac{\sum(C_0 - Ci)}{\$_i}$.

For Pest A (C_0 - C_i) lower bound = 0.2 – 0.3 = -0.1
upper bound = 0.4 – 0.1 = 0.3

Note that the lower bound is negative, implying the possibility that consequences of Pest A might be worse under strategy *i* than the do nothing scenario.

For Pest B (C_0 - C_i) lower bound = 0.5 – 0.5 = 0
upper bound = 0.8 – 0.4 = 0.4

Now let's say the uncertain estimate for the cost of implementing strategy *i* is [$0.5M, $2M]. Then

E_i lower bound = (-0.1 + 0)/2 = -0.05
upper bound = (0.3 + 0.4)/0.5 = 1.4.

Reporting only best estimates assumes decision-makers are risk-neutral. Many decision contexts and many decision-makers are not indifferent to the possibility of outcomes that exceed or fall short of expectations. Let's say the results of interval arithmetic calculations for our three strategies *a*, *b* and *c* and three pests *x*, *y* and *z* are as shown in Figure 11. A risk-averse decision-maker seeks to avoid the worst possible outcomes, so the lower bounds are especially relevant. The preferred strategy is the one with the highest lower bound - strategy *c*. A risk-seeking decision-maker looks closely at upper bounds and may elect to implement the strategy that has greatest exposure to the possibility of windfall outcomes. That is, the strategy with the highest upper bound (strategy *b*). The risk-neutral decision-maker looks only at best estimates, where *a* is the preferred strategy.

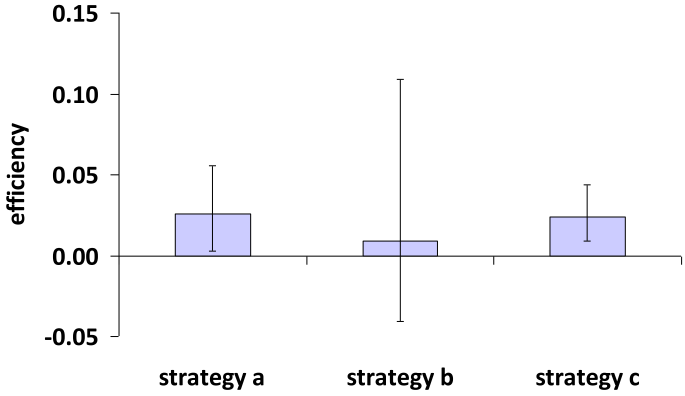


Figure 11. Best estimates (bars) and plausible bounds (whiskers) for the efficiency metric, E_i, calculated for each strategy.

An alternative approach

The efficiency metric is a useful numerical descriptor of the merit of alternative strategies. But it does not make the components of the metric readily apparent to decision-makers. The weakest aspect of the metric is its reliance on global weights to describe (linear) trade-offs in fundamental objectives. Decision-makers will be sensitive to the specific context of individual decisions (Goldstein 1990; Pidgeon and Gregory 2004) and may elect to weigh attributes differently, at least informally. The automated use of global weights will likely lead to ill-considered decisions. An alternative approach is to consider the consequence table directly and avoid formal numerical specification of trade-offs and the calculation of opaque metrics.

Let's say the expected impacts and costs under the do nothing scenario and three alternative strategies are as described in the consequence table below (Table 22a). The effectiveness (and cost) of each strategy relative to the do nothing scenario is simply the difference between expected consequences in the presence and absence of that strategy (i.e. $C_i - C_0$; Table 22b).

The components of the efficiency metric are captured in Table 22b. All that is missing are the weights assigned to each fundamental objective. But we need not formally employ weights to make sensible decisions that are cognisant of key trade-offs. There are often opportunities to simplify a consequence table to expose these key trade-offs through identification of dominated alternatives and redundant objectives (Hammond et al. 1999).

From Table 22b we can see that on all elements of the decision problem Strategy 1 outperforms Strategy 3. That is, Strategy 3 is strictly dominated by Strategy 1 and can be removed from further consideration. Alternatives need not be 'strictly' dominated to qualify for removal. 'Practical' dominance is a more useful criterion. Business impacts then become a (more or less) redundant objective. Both Strategy 1 and 2 have essentially the same risk return for business ($214M and $216M, respectively). It can be removed. The decision problem then reduces to a trade-off between the better performance of Strategy 2 on amenity and environmental objectives against the cheaper costs of implementation of Strategy 1 (Table 22c). Most decision-makers will not require formal numerical specification of trade-offs to make a reasonable and defensible decision in this circumstance.

Table 22 (a). Expected consequences and costs under three strategies and a do nothing scenario.

	Do nothing	Strategy 1	Strategy 2	Strategy 3
Business ($M)	$230	$16	$14	$33
Amenity (0 - 100)	70	48	6	56
Environment (# species)	192	149	138	178
Expected cost ($M)	$0.8	$61.2	$95	$67.9

Table 22 (b). Expected change in consequences for each strategy relative to doing nothing.

	Strategy 1	Strategy *2*	Strategy *3*
Business ($M)	-$214	-$216	-$197
Amenity (0 - 100)	-22	-64	-14
Environment (# species)	-43	-54	-14
Expected cost ($M)	$60.4	$94.2	$67.1

Table 22 (c). Simplified consequence table after removal of dominated alternatives and redundant criteria.

	Strategy 1	Strategy *2*
Amenity (0 - 100)	-22	-64
Environment (# species)	-43	-54
Expected cost ($M)	$60.4	$94.2

Note that this approach will only be viable where the number of fundamental objectives is reasonably small. Informal trade-offs over more than four or five objectives are likely to be beyond the cognitive and emotional capacity of most decision-makers (Payne et al. 1993).

3.3 Application to Pest Risk Assessment (PRA)

The elements of the decision problem for selection of actions and strategies are equally relevant to PRA. However the decision frame concerning the risk posed by import of a new commodity is a little different. The decision does not directly concern assessment of the merit of alternative management actions. Rather, the decision is binary – allow or disallow trade.

International rules governing trade require signatory nations to be least trade restrictive, consistent with a sovereign right to specify an appropriate level of protection (ALOP). A decision to disallow trade is only warranted where a reasonable set of alternative measures (or strategies) has been considered, and all fail to provide returns that reduce risks to a point that satisfies ALOP. In short, international rules oblige consideration of one or more alternatives for risk management (that may include 'do nothing'). The obligation extends to identifying the strategy i that minimises overall expected consequences (i.e. identify $min\ C_i$). Trade is only disallowed where $min\ C_i$ > ALOP.

The critical difference between PRA and the measure of efficiency described above is in the way that the costs of risk management are incorporated. Risk return per unit expenditure (i.e. E_i) is irrelevant in the context of international trade. Instead, the World Trade Organisation allows the anticipated costs of risk management to be included directly in the characterisation of overall expected consequence, C_i (see Table 10). The alternative that minimises C_i is that which minimises the sum of both management costs and pest impacts (Yokomizo et al. 2009).

Incorporating risk management costs into our characterisation of expected consequence under any management scenario *i* requires revisiting fundamental objectives and weights. Table 23 extends Table 12 to include an objective of minimising the costs of risk management (measured in $M). It assumes that the monetary costs of risk management are equally as important as the monetary costs borne by business as a consequence of pest invasion.

Table 23. Swing weights for four fundamental objectives relevant to PRA.

Objective	Best	Worst	Rank	Weight	Normalised weight
Minimise business impacts	0	$20 000 M	2	80	80/310 = 0.26
Minimise amenity impacts	0	100	3	50	50/310 = 0.16
Minimise environmental impacts	0	2,000 species	1	100	100/310 = 0.32
Minimise costs of risk management	0	$20 000 M	2	80	80/310 = 0.26
				Sum = 310	Sum = 1.00

The application of these weights is identical to the way in which weights were used to calculate standardised expected consequence under any strategy *i* in section 3.2. Estimation of expected consequences (including costs of risk management) needs to again consider the probability of encountering the four states of the biosecurity continuum (E', EE', EES' and EES). With some loss of resolution, calculations can utilise the qualitative descriptors of probability and impact employed in the current protocol (Biosecurity Australia 2009), so long as assessors have a clear understanding of the corresponding numerical value of these descriptors. For the purposes of illustration here we use the values shown in Table 24.

Table 24. Numerical values assigned in this report to verbal descriptors of (a) probability and (b) impact.

(a)

Probability	**Value**
Negligible	0.000001
Extremely low	0.0001
Very Low	0.01
Low	0.1
Moderate	0.5
High	0.9

(b)

Impact	**Business**	**Amenity**	**Environment**	**Risk management**
A	$0.1M	0.0005	0.01 species	$0.1M
B	$1M	0.005	0.1 species	$1M
C	$10M	0.05	1 species	$10M
D	$100M	0.5	10 species	$100M
E	$1 000M	5	100 species	$1 000M
F	$10 000M	50	1 000 species	$10 000M
G	$20 000M	100	2 000 species	$20 000M

Now let's say there is a decision to be made about a new commodity that may carry a fungal pathogen to which *Eucalyptus* is highly susceptible. The pathogen could have non-trivial impacts on the forest industry, forest ecosystems, and landscape amenity. If the risk posed by the fungus is considered to be greater than 'very low' then Australia's appropriate level of protection (ALOP) has been breached and trade in the associated commodity will not be allowed. Again, for the purposes of illustration, let's arbitrarily assign a value of 0.001 for standardised expected consequence as an equivalent descriptor of 'very low'. That is, any strategy *i* that exceeds 0.001 will have failed to satisfy ALOP.

Let's say there are four alternative strategies for risk management:

A1 Chemical control of infestations using phosphate (at the point of establishment prior to spread)
A2 Heat treatment of forest products (at the border prior to entry)
A3 Both measures: chemical control and heat treatment
A4 Neither measure (i.e. do nothing)

No impacts on business, amenity or the environment are anticipated if the pest fails to establish (E' or EE'). Non-trivial impacts can arise at the point of establishment or the point of spread. The costs of risk management depend on the strategy employed. The cost of chemical control of infestations (A1) will only be borne if the pathogen establishes (EES' or EES). The cost of heat treatment at the border will be incurred irrespective of whether or not the pest successfully enters (i.e. E' or EE' or EES' or EES).

Explicit consideration of the four states of the biosecurity continuum provides a sound logic for characterising expected consequence. Those responsible for preparing PRAs need to make the (hypothetical) judgments contained in Table 25 below. These judgments are very similar to those required under the current protocol, with additional estimates required for E', EE' and EES'. Having elicited these judgments the arithmetic for calculating standardised expected consequence is identical to that described in section 3.2, and summarised in Tables 26 and 27.

Table 25. Judgments required of PRA assessors under the proposed framework. (a) The probability of entry establishment and spread under each candidate risk management strategy; (b) impacts on business, amenity and the environment under each state of the biosecurity continuum; and (c) the cost of risk management under each state and strategy.

(a)

Event	probability			
	A1	A2	A3	A4
entry	very low	extremely low	extremely low	very low
establishment|entry	low	low	low	low
spread|establishment	moderate	high	moderate	high

(b)

State	Impact		
	Business	Amenity	Environment
E'	nil	nil	nil
EE'	nil	nil	nil
EES'	C	B	B
EES	D	D	E

(c)

State	Impact – Risk management			
	A1	A2	A3	A4
E'	nil	B	B	nil
EE'	nil	B	B	nil
EES'	D	B	D	nil
EES	D	B	D	nil

The Bayes net below (Figure 12) captures predictions in the white (chance) and grey (deterministic) nodes. The blue node is the decision node containing the four alternatives, and each of the pink hexagons contain the weighted consequences (preference judgments) of impacts A - G. The net is compiled for A2, 'heat treatment at border', showing the standardised expected consequence of -0.0014. The negative sign indicates adverse consequences.

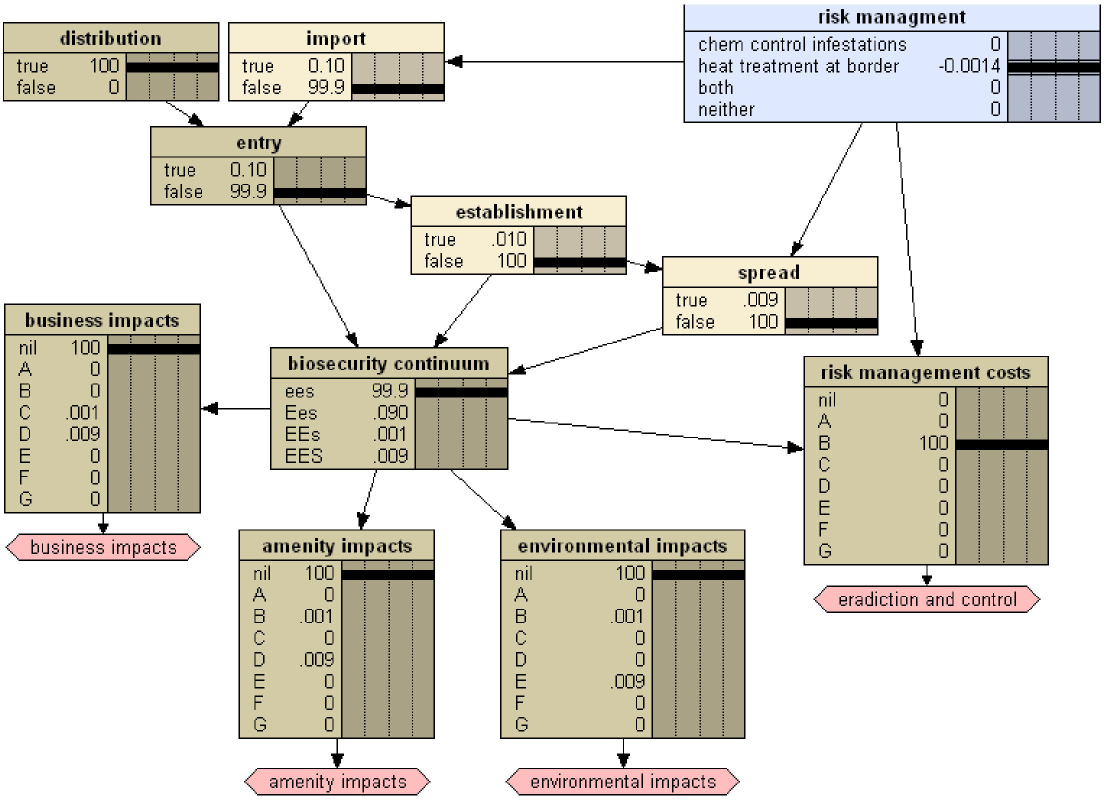


Figure 12. Bayes net for exploring whether or not alternative strategies satisfy ALOP. See text for details.

Table 26. Summed expected consequences under strategy A2 (heat treatment at the border). The probability of each state is calculated from numerical equivalents of the verbal descriptors provided in Table 25. Likewise, consequences are the numerical equivalents of impact codes A-G (see Tables 24a and 24b). The same calculations were made for strategies A1, A3 and A4 (not shown).

State	Probability	consequence (original units)			
		Business	Amenity	Environment	Risk management
E'	0.99900	0	0	0	$1M
EE'	0.00090	0	0	0	$1M
EES'	0.00001	10	0.005	0.1 species	$1M
EES	0.00009	100	0.5	100 species	$1M
Summed expected consequence		$0.0091M	0.00005	0.009 species	$1M

Table 27. Standardised expected consequence for four candidate risk management strategies. All four exceed the nominal ALOP threshold of 0.001.

Strategy	Summed expected consequence (original units)				Rescaled summed expected consequence				Standardised expected consequence
	Business	Amenity	Environment	Risk management	Business	Amenity	Environment	Risk management	
A1	0.05500	0.00025	0.05005	0.10000	0.00028	0.00025	0.00250	0.00050	0.00104
A2	0.00910	0.00005	0.00900	1.00000	0.00005	0.00005	0.00045	0.00500	0.00146
A3	0.00550	0.00003	0.00501	1.00990	0.00003	0.00003	0.00025	0.00505	0.00140
A4	0.09100	0.00045	0.09001	0.00000	0.00046	0.00045	0.00450	0.00000	0.00163
				weight	0.26	0.16	0.32	0.26	

Results for all four alternatives are shown in Table 27. The best strategy (i.e. *min* C_i) is A1, chemical control of infestations, with a standardised expected consequence of 0.00104. Although the costs of risk management under A1 were substantial at an estimated $100M, these costs would only be incurred if the pest established, and the likelihood of this event was estimated to be 0.001 (i.e. Pr{EES'} + Pr(EES}).

None of the alternatives satisfy ALOP. The standardised expected consequence (or risk) of all four exceed 0.001. If the four candidate alternatives can be considered a diligent exploration of the set of possible risk management strategies then it is reasonable to disallow trade in the associated commodity.

3.4 Discussion

Addressing limitations

Maguire (2004) cites two interacting flaws commonly encountered in risk assessment protocols: (a) separating risk assessment from risk management, thus disrupting essential connections between social values and the scientific knowledge necessary to predict the likely impacts of management actions, and (b) relying on expert judgment about risk framed in qualitative and value-laden terms, inadvertently mixing the expert's judgment about what is likely to happen with personal or political preferences. To buffer against these flaws, we proposed a structured decision-making framework that explicitly deals with a probabilistic approach to cause-and effect and multi-attribute analysis to describe and weigh social and organisational values (Maguire 2004). In Section 2.2 we outlined six limitations evident in current protocols used in biosecurity decision-support. In Table 28, we summarise how the proposed framework described in Section 3 can redress these limitations.

Table 28. How the proposed framework deals with the limitations in decision support protocols identified in section 2.2.

Limitation	Approach of proposed framework
Vague formulation of the decision problem	• Define fundamental objectives. • Identify alternatives. • Estimate expected consequences against objectives.
Vague use of language	• Avoid conflating scientific and value judgments. Clearly specify what judgments need to be made regarding predictions and what judgments need to be made regarding preferences. • Use unambiguous attributes to characterise the performance of alternatives under each fundamental objective.
Poor estimation of likelihood in the prediction of expected consequences	• Elicit or model absolute predictions of likelihood and include all relevant states (not just EES).
Confusing means and ends objectives	• Avoid overlaps and redundancies in the set of fundamental objectives.
Assigning arbitrary value judgments (or avoiding value judgments altogether)	• Make the range of expected consequences associated with each alternative and each objective apparent to decision-makers. • Where necessary, elicit range-sensitive preferences using swing weights.
Reluctance to include uncertainty	• Include plausible bounds on estimates of likelihood and consequence and carry uncertainties through chains of calculations.

Qualifying comments

Multi-attribute decision support is increasingly recognised as a sound approach to integrating scientific predictions and social preferences in biosecurity (Maguire 2004, Mourits and Lansink 2007). But it is not a panacea. Common traps in decision-making include (Hammond et al. 2006):

- Anchoring: giving disproportionate weight to initial information received.
- Status-quo: favouring alternatives that maintain business as usual.
- Sunk costs: favouring alternatives that justify flawed decisions of the past
- Confirming evidence: selectively seeking information that is consistent with preconceived ideas.
- Estimating and forecasting: overconfidence caused by over-influence of vivid memories.

The injudicious use of expert judgment for prediction is especially susceptible to these traps. Deliberate and structured cross-examination of expert judgment is critical (Speirs-Bridge et al. 2010).

The elicitation of preferences is emotionally and cognitively difficult. While swing weights buffer against insensitivity to range, the weights themselves should be used only where necessary, and only for guidance. The normative theory of decision-making is based on the preferences of an individual decision-maker. Any attempt to aggregate the weights of multiple decision-makers or stakeholders is difficult. Where consensus is not possible or appropriate the standardised expected consequence scores for alternative strategies should be interpreted cautiously. The decision analyses illustrated in this report offer valuable insight, but not optimal solutions. Well-reasoned and defensible decisions can be made without formal specification of weights. The 'alternative approach' outlined at the end of section 3.2 has much to recommend it (Failing et al. 2007).

Even for individual decision-makers, the elicitation of coherent weights can be difficult. Unstable and non-transitive preferences are commonly encountered (Akter et al. 2008). Robust methods have been developed for the valuation of non-market attributes in benefit-cost analyses (Bennett and Blamey 2001), but the time and resources required to apply these methods may make their routine use in biosecurity decision-making impractical. An alternative approach is to explicitly accommodate uncertainty in preferences. The extension of rough set theory to multi-attribute problems offers one avenue for doing so, and has already been applied in a biosecurity setting (Sikder et al. 2006). Again, there is a trade-off for agencies with limited time and resources between performance and effort.

Decision theory discriminates between expected value (in the absence of probabilistic uncertainty) and expected utility (presence of uncertainty; von Neumann and Morgenstern 1944). The framework we propose does not formally deal with utilities. That is, it assumes decision makers are indifferent to the rank priority of three pests with the following likelihoods and consequences:

0.001 x $1,000 M = $1 M,
0.500 x $2 M = $1 M,
1.0 x $1 M = $1 M.

Under utility theory, a decision-maker can be entirely consistent with normative axioms of rationality if they do not regard these three pests as equal risks.

Finally, a serious omission in the proposed framework is the failure to consider time preference. That is, all else being equal, a pest with the capacity for rapid dispersal over a short time horizon will be a higher priority than one that spreads slowly. Economists routinely apply discount rates to represent time preference. The framework would be considerably improved if it incorporated a well reasoned approach to discounting.

Next steps

We identify four immediate steps needed to progress the decision-making framework presented in Section 3.

1. Identification of methods for predicting consequences associated with fundamental objectives.
Defensible scientific judgments underpin the prediction of consequences. Clear guidance on appropriate approaches to modelling and expert elicitation techniques is needed. This guidance needs to recognise the operational constraints under which biosecurity decisions are typically made.

2. Elicitation of preferences in selected case studies.
The trade-offs made implicitly in current decision-making need to be captured to encourage consistency. Where appropriate the contrasting preferences of stakeholders can be explored to inform compromise solutions and bargaining.

3. Calibration of the framework with the current pest risk assessment protocol.
We assigned an arbitrary threshold for standardised expected consequence supposedly equivalent to ALOP. The proposed framework needs to be calibrated with the current protocol to promote consistency with past assessments.

4. Training
Much of the expertise in biosecurity agencies is in the biological sciences. If the framework is to be used routinely in-house staff will need to supplement their traditional expertise with training in probability theory, risk assessment and multi-attribute decision support. Specific and practical tools where development of competencies could be targeted include:

- Cognitive maps and influence diagrams for formulating problems and capturing ideas of cause and effect
- Strategy tables for developing alternatives that comprise multiple actions.
- Logic trees for identifying the set of relevant states of a system
- Four point elicitation for capturing expert judgment
- Use of consequence tables in decisions involving informal trade-offs
- Use and misuse of methods for eliciting preferences and weights
- Decision-making under uncertainty

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APPENDIX
A primer on Multi-Attribute Decision Theory

The formal description of multi-attribute decision theory that follows is adapted from Bedford and Cooke (2001) and Keeney (2007).

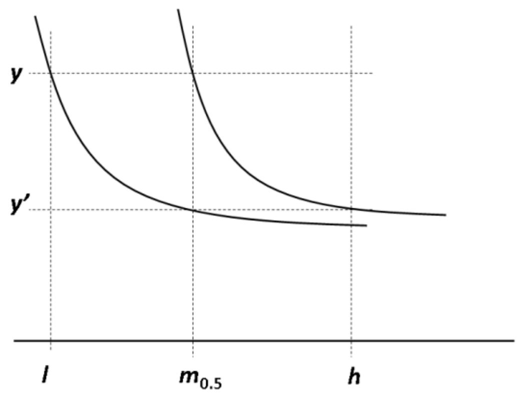
Many decision problems involve multiple objectives ($O_1,\ldots,O_n$) that influence our preference for one course of action over another. The relative achievement of objectives can be described using appropriately selected attributes ($x_1,\ldots,x_n$). The task of multi-attribute value theory is to find a simple expression for the decision-maker's value function v over two or more relevant attributes. The additive value model is commonly used, in the form

$$v(x_1,\ldots,x_n) = \sum_{i=1}^{n} w_i v_i(x_i)$$

where the w_i are the weights and the v_i are so called 'marginal value functions'.

A marginal value function is a value function for any single attribute in isolation. A formal way of eliciting a marginal value function is as follows. Suppose that we want to determine a value function for x_1. Write the vector of attributes exclusive of x_1 as $\underline{y} = (x_2,\ldots,x_n)$. We can pick two values for the attribute x_1, say $l < h$, and arbitrarily assign $v_1(l) = 0$ and $v_1(h) = 1$ (assuming that lower values of the attribute are worse than higher values). We now want to interpolate and find a number $m_{0.5}$ between l and h so that $v_1(m_{0.5}) = 0.5$ (see Figure below). To do this we pick a value for the other attributes, $\underline{y}$, and seek a 'worse' value for the other attributes $\underline{y}'$ so that for some $m_{0.5}$ between l and h,

$(l, \underline{y}) \sim (m_{0.5}, \underline{y}')$, and
$(m_{0.5}, \underline{y}) \sim (h, \underline{y}')$.



Writing $v_{\underline{y}}$ for the weighted sum of the value functions in $\underline{y}$, we then have

$$v_1(l) + v_{\underline{y}}(\underline{y}) = v_1(m_{0.5}) + v_{\underline{y}}(\underline{y}'),$$
$$v_1(m_{0.5}) + v_{\underline{y}}(\underline{y}) = v_1(h) + v_{\underline{y}}(\underline{y}'),$$

which together gives $v_1(m_{0.5}) = 0.5$. In this (laborious and cognitively demanding) way we can interpolate the value function for as many points as desired. The same procedure is required for each attribute.

The approach we used in the body of this report assumed linearity between $v_1(l) = 0$ and $v_1(h) = 1$. It avoids the tedious demands of formal elicitation but may only be reasonable over the local range of consequences associated with small range problems (Keeney and von Winterfeldt 2007). Assuming linearity over the full (global) range of consequences imaginable for biosecurity is a very coarse approximation.

Having obtained marginal value functions we need to weight them. This can be done by using indifferences. Suppose that x_1 and x_2 are the first two attributes, and that $\underline{b}$ is the vector of remaining attributes. Let x_1^* and x_2^* and $\underline{b}^*$ be the attribute values for which the marginal value functions are zero. Then if we can find values $x_1 \neq x_1^*$ and $x_2 \neq x_2^*$ such that

$$(x_1, x_2^*, \underline{b}^*) \sim (x_1^*, x_2, \underline{b}^*)$$

then $w_1 v_1(x_1) = w_2 v_2(x_2)$. Proceeding this way we can get $n - 1$ linear equations relating weights (without loss of generality we can assume the weights sum to 1), and solve for the w_i. Again, the method is laborious and cognitively demanding.

Whatever method is used in their elicitation, the interpretation of the weights is critical. Methods that do not explicitly deal with indifferences are prey to abuse. Users are inclined to specify weights that reflect the relative importance of the attributes, irrespective of the units or the range of consequences relevant to the decision context. But the weights have units because the underlying attribute scales have units. A change of $-w_i^{-1}$ units on scale i is always compensated by a change of $+w_j^{-1}$ units on scale j. Changing the units or range of an attribute *must* lead to a change in the weights.

There are many shortcut methods for eliciting weights (Hajkowicz et al. 2000). Of these, the swing weight method used in the body of this report has been shown to be one of the more effective, both in terms of its efficiency and its insulation against abuse (Fischer 1995).

For the *additive* value model to be valid the attributes must be *mutually preferentially independent*. That is, the value ascribed to any given amount of attribute i cannot be conditioned by the level available of attribute j. Writing the vector of attributes as $\underline{x} = (x_1,\ldots,x_n)$, we will sometimes want to decompose the vector into two sub-vectors: let I be a proper subset of $\{1,\ldots,n\}$, then write $\underline{a}$ for the vector obtained by removing those elements x_i from $(x_1,\ldots,x_n)$ whose index i does not belong to I, and $\underline{b}$ for the vector obtained by removing those elements that do belong to I. The conjoined vector $(\underline{a}, \underline{b})$ contains all the attributes, but possibly in a new order. We call $(\underline{a}, \underline{b})$ a decomposition of $\underline{x}$. We say that the attributes indexed by I are preferentially independent of the others if for all vectors $\underline{a}$ and $\underline{a}'$ we have that

$$(\underline{a}, \underline{b}) \succeq (\underline{a}', \underline{b}) \text{ for some } \underline{b},$$
$$\text{implies } (\underline{a}, \underline{b}') \succeq (\underline{a}', \underline{b}') \text{ for every } b'.$$

The attributes in the vector $\underline{x}$ are mutually preferentially independent if $\underline{a}$ is preferentially independent of $\underline{b}$ for every possible decomposition of $\underline{x}$ into a pair $(\underline{a}, \underline{b})$. Clearly there are an enormous number of conditions $(2^n - 2)$ to be checked to demonstrate mutual preference independence. In practice, the assumption is reasonable if the set of fundamental objectives is consistent with the following properties (Keeney 2007):

- Complete – all of the important consequences of alternatives in a decision context can be adequately described in terms of the set of fundamental objectives.

- Non-redundant – the fundamental objectives should not include overlapping concerns.
- Concise – the number of objectives should be minimal.
- Specific – each objective should be specific enough so that consequences of concern are clear and attributes can readily be selected or defined.
- Understandable – any interested individual knows what is meant by the objectives.

Where objectives satisfy these properties there is a strong case for use of simple weighted summation.