Biosecurity

A Systems Perspective

Edited by Susan M. Hester, Lucie M. Bland, Edith Arndt, Sana Bau, James S. Camac, Evelyn Mannix, Raphaël Trouvé and Andrew P. Robinson

First published 2024

ISBN: 978-1-032-18168-4 (hbk)
ISBN: 978-1-032-18169-1 (pbk)
ISBN: 978-1-003-25320-4 (ebk)

Chapter 9

Resource Allocation

Using Economic Principles to Prioritise Projects and Allocate Biosecurity Budgets

DOI: 10.1201/9781003253204-13

The funder for this chapter is
University of Melbourne, School of Biosciences, Centre of Excellence for Biosecurity Risk Analysis (CEBRA), Australia

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

9 Resource Allocation

Using Economic Principles to Prioritise Projects and Allocate Biosecurity Budgets

Lucie M. Bland, Christine Li, Tom Kompas, Long Chu, Hoa-Thi-Minh Nguyen, and Susan M. Hester

ABSTRACT

Biosecurity budgets are unlikely to ever be adequate to reduce all threats to acceptable levels. Because of this, biosecurity agencies must decide on the relative importance or urgency of a large number of biosecurity risks, and which of these will be mitigated using the finite resources available. In this chapter, we outline methods for resource allocation based on the economic principle of value for money. Cost-efficient prioritisation involves understanding the costs and benefits of interventions across the range of pests and diseases that could be funded from a fixed budget. We outline the pros and cons of different prioritisation methods (including net present value, benefit-cost ratio, and optimisation) and assess when each method can lead to efficient budget allocation, depending on the decision context. Finally, we outline barriers and opportunities to increase the uptake of economic principles by biosecurity agencies. When economic principles are followed, biosecurity agencies can undertake the risk-reducing activities that provide the best "value for money" for taxpayers and the community.

GLOSSARY

Prioritisation The process of deciding which projects or activities are most important to fund and undertake. Prioritisation should be based on the economic principle of cost efficiency (i.e. value for money).

Cost efficiency vs cost effectiveness An activity is economically efficient if no other use of resources would yield a higher value to the community. Conversely, an activity is economically inefficient if its costs exceed its benefits or if it can be shown that resources could be used to produce something of higher value (Productivity Commission 2013). Cost efficiency should not be confused with cost effectiveness, which is the lowest cost approach to a specific output. In practice, cost efficiency is a higher standard to meet than cost effectiveness. A cost-effective activity is not necessarily cost-efficient, but a cost-efficient activity is also cost effective.

Costs and benefits The costs of a biosecurity activity refer to the human, monetary, or other resources need to implement the activity. The benefits of an activity refer to the value of the economic, environmental, and/or societal damages (impacts) that will be avoided if the activity is successful.

Discounting Allows costs and benefits that arise through time to be transformed into a comparable unit (namely their present value). Discounting accounts for the

DOI: 10.1201/9781003253204-13

fact that a dollar received or spent today is worth more than a dollar in the future, as today's dollars could be invested and earn interest. Higher discount rates erode future benefits and costs more rapidly than lower discount rates.

Benefit-cost analysis (BCA) Encompasses a range of methods concerned with comparing the costs and benefits of activities. BCA outputs include the net present value (NPV) of benefits and benefit-cost ratios (BCR). Within a BCA, output measures are used to decide whether to invest in a project and/or prioritise projects.

Optimisation Describes the maximisation or minimisation of an objective, subject to one or more constraints. For example, a regulator may want to determine the combination of projects that minimises the total costs of impacts and activity costs (the objective) subject to a particular budget (the constraint). Optimisation problems are typically solved using mathematical programming techniques.

Returns to scale (RTS) Describe changes in extra benefits as expenditure increases. The three basic types of returns to scale are increasing, decreasing, and constant. For many biosecurity activities, returns to scale are expected to be decreasing (i.e. diminishing returns from extra expenditure).

INTRODUCTION

Biosecurity agencies have the difficult task of deciding how their budgets should be allocated to reduce, mitigate, or eliminate threats from pests and diseases. As biosecurity budgets are unlikely to ever be adequate to reduce all threats, choices must be made between many investment possibilities (Craik, Palmer, and Sheldrake 2017). The challenge for decision makers is deciding how to efficiently allocate limited monetary, human, or other resources to activities that will generate the best outcomes for the economy, society, and/or the environment (Epanchin-Niell 2017). Resource allocation therefore involves deciding on the relative importance or urgency of a large number of biosecurity risks.

The prioritisation task required to reduce biological harms is complex and occurs once biosecurity managers have identified, analysed, and evaluated risks (see Chapter 3. Anticipate). Managers are asked to prioritise budgets for a range of situations, such as prioritising consignments for screening at the border (see Chapter 5. Screen), selecting geographical areas for early detection surveillance (see Chapter 6. Detect) or allocating response budgets following an outbreak (see Chapter 7. Prepare, Respond, and Recover).

In practice, biosecurity agencies rely on historical legacies, simple rules-of-thumb, or the opinions of stakeholders (e.g. biosecurity managers, experts, or industry leaders) to select management activities or threats to address (Fox and Gordon 2004; Heikkilä 2011; Kompas et al. 2019). Biosecurity funds can be allocated in the same way they have been in previous years, as is typically the case in Australia's national biosecurity agency (Tongue 2020). Or, program funds can be allocated equally across government groups, as used to be the case in the Florida Department of Environmental Protection (Kim et al. 2007). Agencies also allocate funding as a result of political pressure, the visibility of the invasive species and its perceived impacts, co-funding availability, management experience, and pressure from lobby groups (Virtue 2007). Decisions made in these ways tend to lead to significant biases towards preventing some threats compared to others (Cook et al. 2011).

Some biosecurity agencies use risk assessment frameworks to allocate biosecurity budgets (see Chapter 3. Anticipate). Most frameworks incorporate a risk matrix in which likelihood and consequence (derived from published evidence, expert knowledge, or models) are combined to generate risk assessment results (e.g. negligible, low, medium, high, or extreme risk). Within these frameworks, the species deemed to pose the highest risk are often considered the highest priority for funding (see Hester and Mayo 2021 for a review). However, relying on risk rankings resulting from these assessments to allocate biosecurity budgets may not lead to desired outcomes, because risk assessments focus on threats and not on the activities used to manage those threats. Risk frameworks or rankings provide little to no information on the “value for money” of proposed projects—that is, the extent of risk reduction achieved from investing in a project, or whether one project should be funded over another. Risk assessments also do not give information on the total amount of expenditure needed to reduce risk to a particular level (Kompas et al. 2019). Because subjective opinions and risk rankings ignore value for money, resource allocation based on either of these methods results in economically inefficient decisions that do not achieve the highest benefits for the money spent.

Given increasing pressures from global trade and travel, human population growth, and climate change, resources invested in biosecurity activities will need to increase at an even faster rate to ensure absolute risk remains identical (Hulme 2009; IGB 2019). Predictions from the former Australian Government Department of Agriculture, Water and the Environment showed that increasing investment into biosecurity threefold by 2025 would not keep residual risk at 2014–2015 levels (Craik et al. 2017). This budgetary pressure does not result from a lack of knowledge about managing risks, but rather, from an inability for budgets to be increased enough to manage risks using the “business as usual” techniques described above. Government agencies also administer public funds under a culture of high scrutiny and accountability (Bossuyt, Shaxson, and Datta 2014; Chouinard 2013). Arguably, biosecurity agencies need to demonstrate that taxpayer dollars are spent in an economically efficient way to achieve the intended objectives of a biosecurity system—namely, to minimise the negative impacts of pests and diseases on the economy, environment, and community.

In this chapter, we summarise how economic efficiency can be achieved when allocating biosecurity budgets. We focus on the so-called *ex-ante* problems, that is, those comparing prospective projects rather than assessing the performance of past projects (*ex-post* problems). We summarise the types of data needed to prioritise biosecurity activities, including data on the costs of management activities, the benefits (avoided damages) they provide, their return to scale, the types of projects being compared, and economic discounting. We then review different approaches to prioritisation, including benefit-cost analysis (BCA) and optimisation. Based on data availability and the problem at hand, we outline how a decision maker can select a prioritisation method that achieves economic efficiency. Finally, we review current barriers and potential solutions to improving the uptake of economic principles in biosecurity.

INFORMATION UNDERPINNING RESOURCE ALLOCATION

Achieving cost-efficient allocation of biosecurity budgets involves understanding the costs of management activities and how much risk can be reduced by spending money on an activity.

COSTS

Generally, the costs of biosecurity activities can be classified into operating costs (e.g. personnel, consumables) and capital costs (e.g. infrastructure). This requires a breakdown of each activity into the time it is estimated to take, the geographical area over which it will be applied, the number of people required to carry it out, and the materials they will require. These estimates are then multiplied by their per-unit cost, and the costs of all activities are summed. For example, the administration of a weed eradication programme can involve funding a project coordinator, an administration officer, and on-site expenses such as office accommodation, computer equipment, telephone, internet use, and other minor consumables. Search-and-control processes involve labour to cover the potentially invaded area, flagging tape, herbicide, and the cost of travelling to and from sites (Hester et al. 2010).

Costs should be estimated for each year of the project lifespan, and in some cases beyond, to capture the entire timeframe over which damages may occur. When an agency needs to determine resource allocation across a set of candidate projects, only expenditures incurred from the same pool of funds should be accounted for. Local intervention or control costs (e.g. pesticide use) incurred by other parties such as producers and trade losses are not included in cost accounting, but they are included in the accounting of benefits in terms of avoided impacts.

BENEFITS

The benefits of an activity are the impacts (damages) that are likely to be avoided by implementing the activity. Benefits are compared to a base case or counterfactual—the situation that would most likely occur if no action was taken. The calculation of benefits considers the timing and extent of anticipated impacts (Summerson, Hester, and Graham 2018). This requires knowledge of the (often uncertain) relationship between the management activity and reduction in impacts. In recent decades, impact calculations have increased in sophistication by incorporating spread modelling. Pest or disease spread is simulated over time with and without the biosecurity activity and incorporated into benefits—here, the avoided impacts—and costs (see Box 9.1 and Chapter 14. Map).

Impacts may be classified as economic (e.g. production, revenue, and trade losses), environmental (e.g. native species declines), or societal (e.g. human health, infrastructure, or culture; see Chapter 3. Anticipate). Market impacts are comparably easy to calculate because prices reflecting value are readily available. The environment provides important ecosystem goods and services as well as cultural and recreational values often perceived to be priceless. Monetising environmental damages can be difficult, because environmental goods and services are not traded in markets and no market price is available. However, if the value of protecting the environment from the impacts of pests and diseases is not expressed in a common, monetary unit of measure, then this value can be implicitly discounted in resource allocation. Various non-market valuation methods are used to infer the value of non-market impacts (Emerton and Howard 2008). The monetised value of total

BOX 9.1. THE VALUE OF AUSTRALIA'S BIOSECURITY SYSTEM

A project by the Centre of Excellence for Biosecurity Risk Analysis (CEBRA) focused on estimating the value of Australia's biosecurity system (Dodd et al. 2020). The value of the Australian biosecurity system was defined as the difference between benefits under the status quo (biosecurity system "on") and a counterfactual (biosecurity system "off").

Dodd et al. (2020) estimated the value of benefits from 16 asset classes protected by the biosecurity system (namely primary production, ecosystem services, cultural assets, infrastructure, and other assets). The authors estimated the decline in asset values that would occur if exemplar pests and diseases across 40 functional groups enter, establish, and spread. The spatially explicit (2.5 km × 2.5 km resolution), bio-economic simulation model was run over 50,000 simulations for both the biosecurity system "off" and system "on" scenarios to model the arrival, spread, and impact of threats over 50 years, discounted to net present value (NPV).

The total flow of benefits arising from assets at risk was calculated as A$5.696 trillion over 50 years. Without a biosecurity system, approximately $672 billion in damages could be expected, but with a biosecurity system that costs $10 billion, these damages are expected to be reduced to $347 billion, resulting in a benefit of $325 billion (= $672 − $347 billion; see Figure 9.1). The NPV of Australia's biosecurity system is therefore estimated to be around $315 billion at an average benefit-cost ratio (BCR; return on investment [ROI]) of 30:1. Accounting for uncertainty, the 95% intervals of the NPV and BCR are $156–467 billion and 15–45:1, respectively.

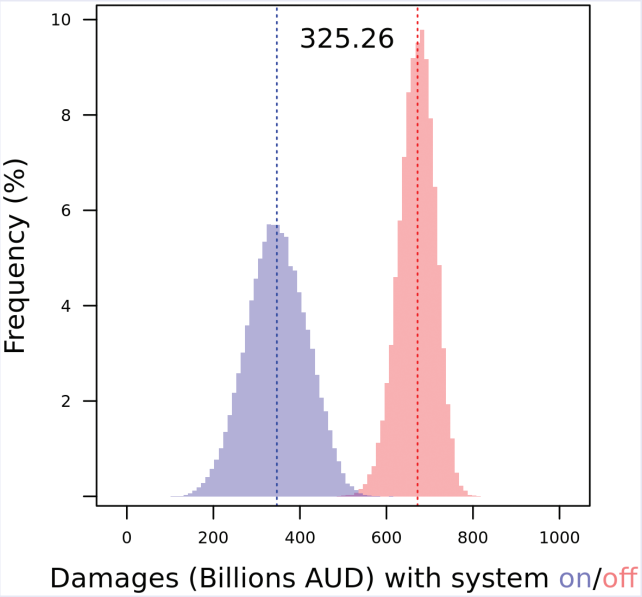

FIGURE 9.1 Damages expected over 50 years in Australia with the biosecurity system "on" (blue) or "off" (red). The dotted lines indicate median damages from 50,000 simulations for each scenario. Median avoided damages (benefits) were estimated to be A$325 billion. (Reproduced with permission from Dodd et al. 2020).

benefits from market and non-market impacts is considered the amount that affected parties are willing to pay to avoid impacts or willingness to receive as compensation for impacts from the pest or disease, although cost-based approaches can also be used (e.g. based on restoration cost or avoidance cost). In some cases, it may only be necessary to assess the monetary value of a subset of impacts (e.g. market impacts) to demonstrate a project's cost-effectiveness relative to the costs of intervention (Cacho et al. 2008; Regan et al. 2006).

Discount Rate

Economic analysis often accounts for benefits and costs that occur over a time horizon spanning multiple years. When costs and benefits are compared at different points in time, costs and benefits must be normalised to 'present value' terms through *discounting* (Hester et al. 2013). The present value is the equivalent value today of a future benefit or cost. By discounting, we acknowledge that a dollar received today is worth more than a dollar received tomorrow (via inflation); today's dollar could be invested and earn interest. The formula for discounting when time is measured in discrete periods (e.g. years) is:

$$PV = FV\frac{1}{(1+r)^t} \quad \text{(Eq. 9.1)}$$

where PV is the present value of a future value FV received in time period t at a discount rate r, which is assumed to be constant over time. Time is generally measured in years, with $t = 0$ representing the current year. Discrete discounting assumes all cash flows happen at the end of the year, while continuous discounting assumes cash flows occur continuously throughout the year (see Harrison 2010 for additional information about discounting).

Discounting reduces the value of costs or benefits of an activity, with the level of reduction depending on the discount rate and the number of years before society accrues the costs or benefits Harrison (2010). Higher discount rates erode future benefits and costs more rapidly than lower rates. Natural and social capital that are often counted in biosecurity analyses are not created or depleted in the same way as built capital, and their values may even increase over time, implying that very low discount rates may be appropriate (Costanza et al. 2021). Following, in the context of biosecurity economics, we recommend a discount rate of $r = 0.03$ for environmental assets and $r = 0.05$ for financial assets.

Returns to Scale

The costs and benefits of activities should be measured along the appropriate scale of effort for the project (e.g. time, geographic scale, and/or activity intensity). Many biosecurity activities can be scaled to achieve different levels of effort, for example to increase the area covered for early detection surveillance or to increase the number of traps per unit area. When deriving the costs of a biosecurity activity, the unit cost of control may vary with the scale of the project. These variations include where: projects have large up-front costs (e.g. infrastructure); decreases in unit costs may occur when activities are applied at large scales (e.g. bulk equipment purchases); or some activities may increase in unit cost when applied at very large scales (Epanchin-Niell and Hastings 2010).

Similarly, changes in benefits may vary with the scale of a project, such as when large benefits are only accrued after a certain level of investment or when extra benefits taper off as expenditure increases. For example, when inspecting air containers for the presence of an insect pest, a biosecurity agency will typically inspect the containers whose histories indicate they are more likely to be contaminated (Robinson et al. 2015). The cost of inspecting a container is fixed, but the benefit from each additional inspection declines as each extra container is less and less likely to be contaminated.

Increases or decreases in extra (marginal) costs and/or benefits with the scale of an activity lead to non-linearities in the relationship between costs and benefits. Returns to scale (RTS) describe changes in extra benefits as expenditure increases (i.e. the slope of the benefit-cost curve). The three basic types of RTS are constant, decreasing, or increasing, corresponding to whether increasing expenditure by a certain amount (e.g. 10%) leads to a marginal (extra) benefit of 10%, less than 10%, or more than 10%, respectively (Figure 9.2).

For many biosecurity activities, RTS is expected to be decreasing, leading to diminishing returns on extra expenditure, because early actions tend to focus on low-hanging fruit while further investment deals with more difficult tasks (Hauser and McCarthy 2009; Kompas, Chu, and Nguyen 2016). Furthermore, diminishing RTS occurs where pest damages irreversibly degrade assets and limit the benefits of additional control and restoration. An ecosystem may recover as the local pest population declines, but at a decreasing rate and never to its full pre-infestation function.

In practice, estimating the slope of a benefit-cost curve requires data on the "value-add" of benefits from additional spending at each level of expenditure. As these marginal benefits are usually sensitive to the specific threat, ecosystem, region, and management activity, quantitative estimation involves spread and population dynamics modelling (see Chapter 14. Map) or structured expert elicitation (see Chapter 12. Elicit). When data are not available to estimate the benefit-cost curve of an activity on a continuous scale, the costs, and benefits of individual project "blocks" (subsets) can be valued instead (see Table 9.4).

Project Mix

When a regulator intends to optimise resource allocation across multiple projects, they should understand the relationship of projects and activities to one another. Projects may be mutually exclusive if

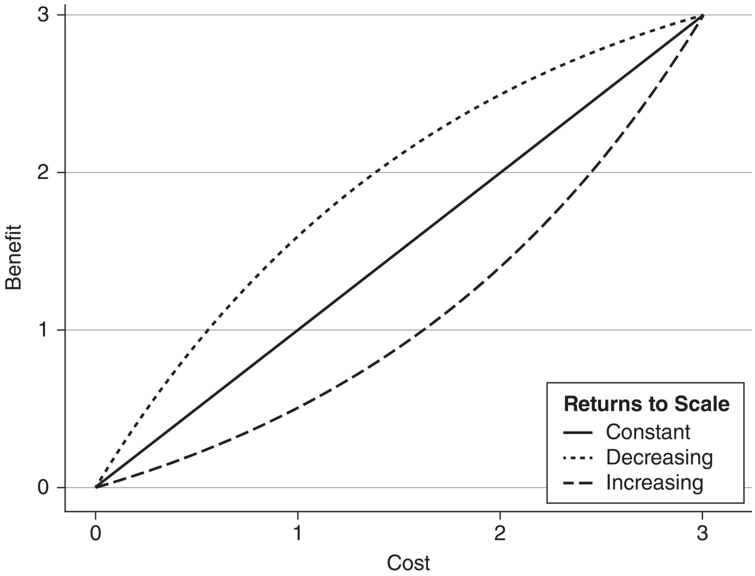

FIGURE 9.2 Benefit-cost curves for three basic types of returns to scale (RTS): Constant, decreasing, and increasing. Decreasing returns to scale is commonly observed for biosecurity activities.

alternative activities aim to achieve the same objective. For example, to contain the spread of foot-and-mouth disease (FMD), project A may involve implementing close-contact (ring) vaccination of cattle, sheep, and pigs, whereas project B may implement ring vaccination of cattle only, hence the two projects cannot be funded or conducted simultaneously. Projects may be independent (unrelated) when they achieve different objectives, and any combination of projects may be included in a prioritised list of projects. For example, project B (ring vaccination of cattle) may be implemented alongside project C, which focuses on improving diagnostic capacity. Due to the complexity of biosecurity systems, projects and activities can show complex relationships of mutual exclusion or independence, which must be accounted for when selecting the most appropriate method for allocating biosecurity budgets.

RESOURCE ALLOCATION METHODS

Benefit-Cost Analysis

BCA involves comparing the costs and benefits (avoided impacts) of a management activity. BCA is the standard method for evaluating the cost-effectiveness of response options when managing pest and disease incursions (Hester et al. 2013). For example, BCA has been used to compare control options for the marine carpet sea squirt (*Didemnum vexillum*; Coutts and Forrest 2007), to assess program funding to control the red imported fire ant (RIFA; *Solenopsis invicta*) in Australia (Kompas and Che 2001), and to compare different intervention strategies for RIFA (Hafi et al. 2014). Summerson et al. (2018) provide general guidelines to apply BCA to determine whether it is worth investing in a response to an invasive species (Table 9.1); these are demonstrated in Box 9.2.

Net Present Value

The sum of discounted costs and benefits is expressed as NPV as follows:

$$NPV = \sum_{t}^{T} \frac{B_t - C_t}{(1+r)^t} \qquad \text{(Eq. 9.2)}$$

TABLE 9.1

Steps Required in a BCA of an Intervention to Reduce the Impacts of a Pest or Disease Incursion.

Step	Actions
1	Specify the intervention activity/activities and the base case (counterfactual) where the threat spreads unmanaged
2	Determine the costs of the intervention activity/activities
3	Identify the likely impacts from an unmanaged incursion
4	Predict impacts over time
5	Assign dollar values to impacts with market and non-market valuation
6	Discount and compare costs and benefits (avoided impacts) of activities
7	Calculate costs and benefits using net present value (NPV)
8	Run a sensitivity analysis for uncertain variables
9	Decide on an activity to implement

Source: Modified from Summerson et al. (2018) and Boardman et al. (2018).

where B_t and C_t represent the benefits and costs, respectively, that accrue in year t, r is the discount rate, and T is the time horizon of the evaluation. When NPV is positive, a proposal is considered to be economically efficient, and the community would be better off from its implementation. When two or more mutually exclusive projects are being considered, the project with the highest NPV is chosen.

BOX 9.2. HYPOTHETICAL EXAMPLE OF BCA USING NPV

The Asian green mussel (*Perna viridis*) is listed on Australia's Priority Marine Pest List (MPSC 2018) because of the significant economic (market) and environmental (non-market) impacts it is associated with, including direct impacts on vessel performance, fouling (e.g. industrial plants, power stations, desalination plants, water inlets, and sewage outlets), poisoning, and outcompeting native species (Murphy and Paini 2010).

In the hypothetical invasion scenario described in Summerson et al. (2018), Asian green mussels were discovered on a vessel arriving in Cairns in Queensland, Australia. The vessel returned to Cairns after travelling to other coastal locations in Queensland and in Darwin (Northern Territory, Australia) and Singapore. Subsequent investigations also found the mussel at the Gladstone port and on an artificial structure in Brisbane, Queensland.

Based on initial delimitation surveys, it was deemed technically feasible to eradicate the incursion. Only one intervention option (eradication) was selected in **step 1**, requiring five activities: in-water surveys of port infrastructure in (1) Cairns and (2) Gladstone to determine whether the mussel had established a founder population (and thus whether eradication at this port would be required), (3) delimitation surveys in Brisbane, (4) an eradication attempt in Brisbane, and (5) a post-eradication survey in Brisbane. The costs of the response action (**step 2**) were calculated as $137,500 (Table 9.2).

The costs of the response action (**step 2**) were compared to impacts from the unmanaged spread of the mussel (**step 3**), the base case. Predicted negative impacts of the mus-

TABLE 9.2

Costs of Response for the Asian Green Mussel in Queensland in a Hypothetical Scenario

Response Activities		Cost
(i) Cairns survey		$52,000
(ii) Gladstone survey		$25,000
(iii) Brisbane delimitation		$17,000
(iv) Brisbane eradication attempt		$20,000
(v) Brisbane post-eradication survey		$23,500
	Total	$137,500

sel were identified on business activity (fouling on vessels, industrial plants, and power stations), the environment (outcompeting native species and changes to water quality), the public (fouling of recreational vessels), human health (poisoning), and urban infrastructure (fouling of water inlets, water and sewage outlets, and navigation buoys). The geographical extent of impacts (**step 4**) was estimated with a spread model and shipping data (see Chapter 14. Map), which predicted that the mussel could spread 60 km beyond Cairns within 5 years.

Market and non-market valuation estimated impacts of $24.6 million in present value terms (Table 9.3). These are the estimated value of damages (**step 5**) that will be avoided if the response is successful. The focus was on valuing the substantial environmental (non-market) impacts of this pest, in addition to a subset of direct impacts, so other impacts were ignored. It was unnecessary to discount impact and response costs (**step 6**) as they were already in present values.

The NPV (**step 7**) is $24.45 million (= $24,594,114 – $137,500). If non-market environmental impacts were excluded and only market impacts were estimated, then the NPV of the biosecurity response would be much lower ($656,614) and perhaps not be deemed large enough to invest in eradication. To protect substantial non-market values, eradication is the preferred option in this hypothetical scenario (**step 9**).

TABLE 9.3

Valuation of Hypothetical Impacts From Asian Green Mussels in Queensland

Impact		Value ($)
Fouling on vessels (additional fuel consumption for 23 cruise ships)		$174,875
In-water cleaning of fouling in Gladstone		$270,000
Investment in filtering and anti-fouling technology		$100,000
Environmental impact		$23,800,000
Treatment of ballast water		$249,239
	Total	$24,594,114

Benefit-Cost Ratio

Rather than simply assessing a project based on comparing its benefits and costs using subtraction (Eq. 9.1), a project may be assessed in terms of its benefit-cost ratio (BCR), that is, its average ROI:

$$BCR = \frac{\sum_{t=1}^{T} B(1+r)^{-t}}{\sum_{t=1}^{T} C(1+r)^{-t}} \qquad \text{(Eq. 9.3)}$$

where the numerator and denominator represent the present value of benefits and costs, respectively, that accrue in year t, with r being the discount rate and T the time horizon. Projects are selected in order of decreasing BCR until the budget is exhausted (Epanchin-Niell 2017).

For example, the biosecurity Project Prioritization Protocol (Dodd et al. 2017) used the principles of BCR and Noah's Ark framework to allocate funding to eradicate 50 hypothetical plant incursions. Project benefit was defined as a combination of a species' weed risk score, the potential effectiveness of the intervention, and the probability of successfully intervention. Cost was the monetary cost of the project as NPV. Projects were then ranked by BCR, with resources allocated to projects according to their rank, until the budget was exhausted. In this hypothetical scenario, return on public expenditure using BCR ranking was improved by 25% compared to investing based on weed risk assessment scores alone (Dodd et al. 2017). However, investment decisions based on BCR ranking require strong assumptions that may not always be met in biosecurity (see section on *Allocating resources based on overall benefit-cost ratio*). The BCR approach is appropriate when the question is to invest in a project or not invest in a project. When faced with the question of where to allocate additional investments among projects, then we need to use the change in BCR, as discussed below.

OPTIMISATION

Although the hypothetical Asian green mussel example above (Box 9.2) describes a problem of whether to fund a single project, in reality decision-makers are often faced with the question of selecting one (or multiple) project(s) to fund from a broad suite of proposed projects. The remainder of this chapter deals with principles for optimal allocation of resources across multiple projects and more complex examples. Complex decisions to identify the combination, scale, or timing of investments require *optimisation* approaches. Optimisation approaches aim to design the investments or management strategies that will provide the best value for money, which means achieving management objectives in the most economical way or providing the greatest overall net benefits (Epanchin-Niell 2017).

In biosecurity, optimisation approaches have been applied to determine optimal surveillance effort (Kompas et al. 2016; Yemshanov et al. 2015, 2019), optimal stopping time for eradication (Regan et al. 2006), optimal combinations of control measures (Odom et al. 2003), and optimal distribution and release of biological control agents (Nordblom et al. 2002). For example, Kompas et al. (2019) developed a generic optimisation algorithm in the MATLAB software to minimise expected total costs (damages and project costs) when managing invasive species. This tool requires a number of biological and economic parameters to be known, such as the average pest entry interval, size of initial pest entry, spread rate, surveillance and prevention effectiveness, damages, eradication costs, passive detection thresholds, and pest latency periods. To demonstrate the method, Kompas et al. (2019) applied their modelling framework to four invasive pests of concern in Australia: RIFA (*Solenopsis. invicta*), orange hawkweed (*Hieracium aurantiacum*), FMD, and papaya fruit fly (*Bactrocera papaya*). Results from the optimisation showed the size of the budget available influences both the priority given to invasive species and the specific biosecurity measures employed.

When prioritising biosecurity activities, optimisation approaches focus on the additional risk reduction (ΔB) achieved from additional expenditure (ΔC). If the shape of the benefit-cost curve for each candidate activity is known, the unit change in benefit (ΔB) per unit change in cost (ΔC) can be derived. For a single project or mutually exclusive projects, the optimal time to stop funding a project is when the extra benefits are no longer worth the extra costs (ΔB ≤ ΔC). For a portfolio of candidate activities, the activity with the highest extra benefits (ΔB) for each increase in unit cost (ΔC) is iteratively identified until the budget is exhausted, or, for all projects, the extra benefits are not worth the extra costs (ΔB ≤ ΔC). Using principles from economics, an optimal budget allocation is reached when the marginal return from investment (ΔB/ΔC) across all activities has been equalised.

In Figure 9.3, the exact optimum for resource allocation is identified by iteratively allocating every unit of cost (ΔC) to the action with the greatest additional benefit (ΔB). Project A exhibits constant RTS, meaning that a one-unit increase in cost results in a one-unit increase in benefits at any point along the benefit-cost curve. Projects B and C show diminishing returns, meaning that their marginal ROI (ΔB/ΔC, the slope of the pay-off curve at ΔC) differ at each level of investment. An optimal resource allocation outcome requires switching between projects with the steepest slope at each point along the curves.

Assuming the total funding available to a regulator is 50 units and considering discrete increases in project funding of 10 units, project C should be prioritised for the first 10 funding units (up to point 1 in Figure 9.3), as project C shows the highest marginal returns at that point. As the slope between 10 and 20 units of funding flattens for Project C, marginal returns from investing further diminish, and the regulator should switch to funding the first 10 units for project B (up to point 2 in Figure 9.3), as project B's slope between 0 and 10 units is steeper than project C's slope between 10 and 20 units. For the next 10 units, and until the budget of 50 units is exhausted, project A should be funded (points 3 to 5 in Figure 9.3). Overall, project A would be allocated 30 units of funding, and projects B and C would be allocated 10 units each.

True optimisation requires going beyond discrete changes in investment (e.g. 10 units of funding) to consider continuous changes along a curve (i.e. each additional dollar or cent). Even if data may not be available to estimate the slopes of all projects at all levels of investment (i.e. the entire shape of all benefit-cost curves), linear approximation can be used to estimate slopes for incremental changes in investment if increments are small enough. The optimisation method described in Figure 9.3 is easy to apply for projects that can be partially funded or scaled up and down as necessary. Projects that need to be funded fully to achieve any outcome will require additional optimisation constraints.

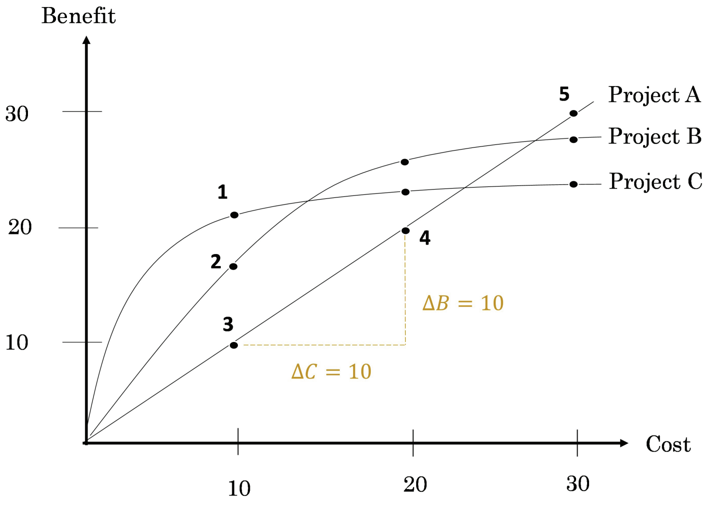

FIGURE 9.3 Conceptual representation of three biosecurity projects with varying benefit-cost curves. Project A shows constant (linear) returns to scale, while projects B and C both show diminishing returns to scale, albeit at different rates.

SELECTING A RESOURCE ALLOCATION METHOD TO ACHIEVE ECONOMIC EFFICIENCY

This chapter outlined different resource allocation methods for biosecurity budgets, including BCA (using the measures of NPV or BCR) and optimisation. In this section, we present the pros and cons of each method and outline when it may (or may not) be appropriate to cost-efficiently allocate budgets.

Allocating Resources Based on Net Present Value

When NPV is used to allocate resources, funding is awarded when NPV is positive (i.e. benefits exceed costs) and when two or more mutually exclusive projects are being considered, the project with the highest NPV is typically chosen.

In the hypothetical example of an invasion by the Asian green mussel outlined in Box 9.2, eradication is the preferred option (compared to doing nothing) because the NPV of the eradication project is $24.45 million (= Benefits – Costs = $24,594,114 − $137,500). Here, it is clear that NPV does not account for the budget constraint (namely whether a budget of $137,500 is available) and whether resources would generate higher value for money if allocated to different projects.

The only circumstance under which it is economically efficient to allocate resources with NPV is when projects are mutually exclusive and the budget is limited (Pannell 2019). This is because NPV allows us to compare the opportunity costs of foregone project versions.

While it is possible to include opportunity costs in the calculation of project BCRs, the ranking of projects is sensitive to the budget level and opportunity costs, and BCRs would need to be recalculated for different budget levels (Pannell 2019). For projects with diminishing returns, it is best practice to first estimate benefit-cost curves to identify the level of investment at which more investment ceases to yield additional benefits ($\Delta B = \Delta C$). Once project budgets have been adjusted to reflect these diminishing returns, NPVs can be calculated and compared.

Allocating Resources Based on Overall Benefit-Cost Ratio

When BCR is used to allocate resources, funding may be justified when BCR exceeds one (1:1) or another ratio selected by the decision maker. Given a set of projects ranked by BCR, decision makers typically proceed top-down, using a threshold where projects with a higher BCR get the entire budget they ask for and projects with lower BCR receive nothing. This all-or-nothing process is often known as the Noah's Ark solution (Dodd et al. 2017). Allocating resources based on the highest BCR makes the implicit assumption that projects' RTS are constant, which is usually untrue or at least should be tested rather than assumed a priori. Noah's Ark solution requires strong assumptions about the shapes and relationships of projects' benefit-cost curves, which are likely to be false in many biosecurity projects.

In Figure 9.4 a, b, two alternative projects, each with declining RTS curves originating from O_1 and O_2, respectively, are proposed against a total budget of 10 cost units. For the sake of illustration, in these examples Project 1 has an overall BCR of 12.6 and Project 2 has an overall BCR of 15.5. Under an overall BCR ranking, Project 2 would secure the entire budget because it has a higher overall BCR (a larger area below the curve). However, allocating the entire budget to the project with the highest overall BCR is not optimal. The optimal allocation that maximises the total benefit from both projects is the intersection of the two RTS curves, where the proportional allocation of the budget is 2:8 in favour of Project 2. This is because the extra benefit that would arise from the 9th And 10th cost units of Project 2 is less than the extra benefit that would arise from the 1st and 2nd cost units of Project 1.

In Figure 9.4 a, b, the BCR ranking is not optimal but is still indicatively right, in that the project with the higher BCR is also the one that is proportionally favoured under optimisation

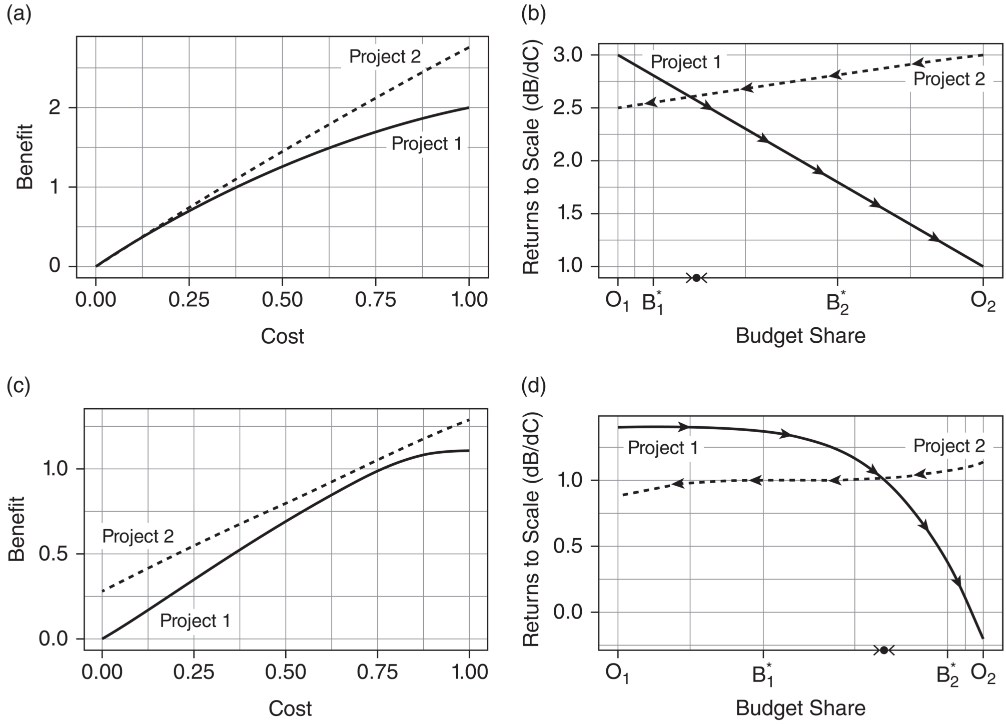

FIGURE 9.4 (a) and (c) Two examples of benefit-cost curves for two competing projects (Projects 1 and 2). (b) and (d) Two examples of returns to scale curves for Projects 1 and 2, with origins at O_1 and O_2, respectively (n.b. the curve for Project 2 starts on the right-hand of the x-axis). The position of the circle on the x-axis indicates when optimal investment switches between Projects 1 and 2. B_1* and B_2* indicate optimal budget shares. (Adapted from Kompas et al. (2019) with permission.)

(Project 2). However, in some cases BCR rankings can give an incorrect signal regarding budget shares.

Figure 9.4 c, d shows a situation where the extra benefit arising from the extra expenditure on Project 1 starts relatively flat before decreasing. Project 1 has an overall BCR of 7.1 and Project 2 has an overall BCR of 8.8. In this case, Project 1 has a lower BCR, but it should have 60% of the budget, directly contrasting its BCR ranking. In this case, allocating by overall BCR is neither optimal nor indicatively right.

The only time it is correct to use the highest BCR to allocate resources is when projects are unrelated (independent) and all of their benefit-cost curves are linear (i.e. constant RTS). The only reason overall BCR rankings are economically efficient in this instance is because the slopes of the curves of each project are identical at each level of effort (cost) and equal to the overall BCR (i.e. $\text{BCR} = \Delta B/\Delta C$).

ALLOCATING RESOURCES BASED ON BLOCKS OF BENEFIT-COST RATIO

Data may not be readily available to estimate benefit-cost curves on a continuous scale to allow for a full optimisation. To approximate benefit-cost curves for unrelated (independent) projects, splitting projects into distinct "blocks" of funding and ranking each block can result in more economically efficient prioritisation compared to using BCR ranks for entire projects. The smaller the funding blocks, the more accurately RTS can be estimated for each additional unit of funding.

Table 9.4 provides an example of BCR block ranking and illustrates its potential superiority compared to overall BCR ranking. Table 9.4a shows the rankings of three projects (C, D, and E)

TABLE 9.4

Comparison of Ranking by (a) Overall Benefit-Cost Ratio (BCR) and (b) Splitting Projects into Blocks and Ranking Individual Blocks by BCR.

(a) Ranking by Overall BCR

	Project C	Project D	Project E
Cost	1	2	7
Benefit	5	7	8
Overall BCR	5	3.5	1.1
Overall BCR ranking	**1**	**2**	**3**

(b) Ranking by BCR Blocks

	Project C	Project D		Project E						
Block	Block 1	Block 1	Block 2	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
Cost	1	1	1	1	1	1	1	1	1	1
Benefit	5	6	1	7	0.5	0.1	0.1	0.1	0.1	0.1
BCR per block	5	6	1	7	0.5	0.1	0.1	0.1	0.1	0.1
Block BCR ranking	**3**	**2**	**4**	**1**	**5**	**6**	**6**	**6**	**6**	**6**

Source: Derived from Kompas et al. (unpub.) with permission.

according to their overall BCR. In Table 9.4b, the three projects are split into individual blocks (1 block for Project C, 2 blocks for Project D, and 7 blocks for Project E). Rankings based on the individual costs, benefits, and BCRs of these blocks show that the first unit of budget should be allocated to block 1 of Project E (and the second unit allocated to block 1 of Project D), despite Project E having the lowest overall BCR (and Project D the second lowest overall BCR). Ranking by BCR blocks accounts, to some extent, for non-constant RTS in projects. The BCR for block 1 of Project E is high (BCR = 7), whereas BCRs for blocks 2 to 7 are less than 1, indicating that funding these blocks would be economically inefficient. These low BCR blocks contribute to the low BCR of project E as a whole.

Under a hypothetical budget of 3 cost units and using overall BCR rankings, a regulator would choose to fund Projects C and D. By splitting projects into blocks and assessing these separately using BCR blocks, a regulator would choose to invest in block 1 of Project E, block 1 of Project D, and block 1 of Project C.

Given a hypothetical budget of 4 cost units, a regulator using overall BCR would still fund projects C and D and would have 1 unit of cost left over, whereas a regulator using a block BCR approach would be able to fully fund projects C and D and block 1 of Project E, generating additional benefit. This example thus illustrates how blocking may also make better use of all funding available.

Allocating Resources Based on Optimisation

When RTS is not constant, it is always best to formally optimise resource allocation by minimising the total costs of impacts and management actions. Even when RTS is constant, optimisation methods can still be used.

The costs of misallocation using other methods such as ranking by overall (average) BCR or NPV can be high when dealing with pest impacts that increase non-linearly with pest population density and/or with time and where management actions are also likely to exhibit nonlinear RTS. Some pests can cause high impacts at low density (e.g. those that trigger export prohibitions at low thresholds), such as weeds affecting wheat crops or FMD (Cook et al. 2012; Yokomizo et al. 2009). Because impacts are incurred in a highly nonlinear way, they are also not likely to be reduced at a constant rate proportional to additional spending. Incorrect allocation by applying simple ranking rules can result in underinvestment towards control and eradication early in the outbreak or underinvestment in measures preventing arrival and establishment. Such resource allocation may lead to impacts that cost more to rehabilitate than the money originally saved (Yokomizo et al. 2009). Conversely, some pests have almost no impacts at low density and with impacts growing only when population densities become large. Incorrectly assuming constant RTS can lead to allocation decisions that waste resources by overinvesting in unnecessary actions early in the outbreak or in early eradication (Yokomizo et al. 2009). Optimisation approaches should thus be used when benefits (avoided damages) are sensitive in variable and non-linear ways to pest density, maximum economic impacts, ecological parameters (such as environmental fluctuations in mortality, density-dependent population recovery, and difficulty of eradication), and management parameters (such as the time-horizon of actions and discount rates; Yokomizo et al. 2009).

Optimisation methods may also be required when combinations of independent projects or combinations of independent and mutually exclusive projects are being considered—the technical detail may be beyond the interest of some readers. Two of this chapter's authors (TK and CL) applied optimisation to assist an Australian State Government in project prioritisation. They developed a spreadsheet-based BCA model for New South Wales Biosecurity & Food Safety that provides an integer programming optimisation approach for prioritising a combination of independent and mutually exclusive projects. If a set of projects are all mutually exclusive, optimisation methods can still be used but may not be necessary (see section on *Allocating resources based on net present value*).

SELECTING A RESOURCE ALLOCATION METHOD BASED ON THE DECISION CONTEXT

Using optimisation methods always ensures resource allocation is cost-efficient, regardless of the specifics of the problem at hand. However, under specific decision contexts, it may be appropriate to use simpler approaches, as these will provide the same results as (or an approximation of) optimisation.

To select an appropriate method, Figure 9.5 shows how a biosecurity resource allocation problem can be broken down into core questions relating to the project mix, assumptions about RTS, and data availability:

- *Projects are mutually exclusive*: Distinct projects could achieve a set objective. Ranking by NPV can be used, regardless of the RTS of projects, as this will provide the same results as optimisation.
- *Projects are unrelated* (*independent*): If the RTS of all projects is constant, ranking by overall BCR is correct and will provide the same results as optimisation. If the RTS of any of the projects is not constant (which is likely to be the case in biosecurity), then ranking with overall BCR will lead to inefficient resource allocation (and ranking may be indicatively wrong; see Figure 9.4b). If RTS is not constant, only optimisation will lead to economically efficient decisions. If data are unavailable to calibrate benefit-cost curves on a continuous scale, ranking by BCR blocks can provide a useful approximation of optimisation results and will be superior to ranking by overall BCR.
- *Projects are a combination of mutually exclusive and independent*: When the project mix includes a combination of mutually exclusive and independent projects, only optimisation leads to economically efficient decisions. If the RTS of all projects is constant (or assumed to be), basic integer programming can be used to solve the optimisation problem.

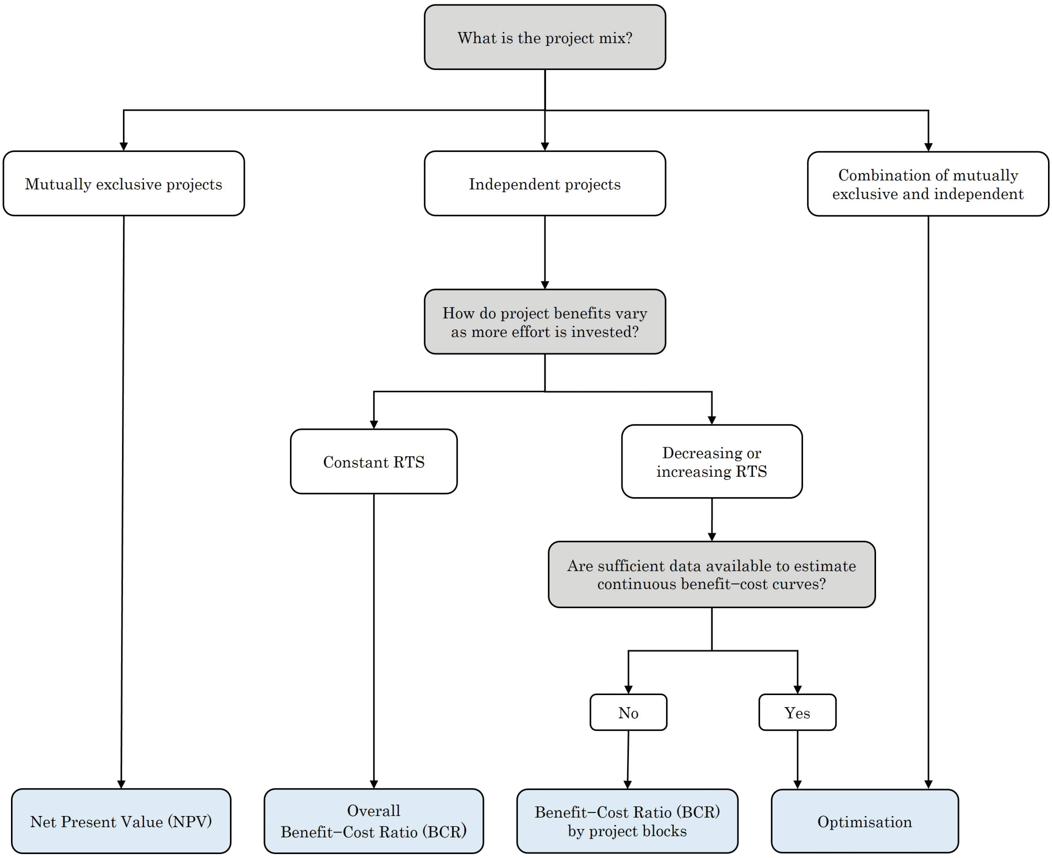

FIGURE 9.5 Decision tree to inform the selection of a cost-efficient resource allocation method in biosecurity. *Abbreviation*: RTS: Returns to scale.

BARRIERS AND OPPORTUNITIES FOR COST-EFFICIENT RESOURCE ALLOCATION IN BIOSECURITY

Under the World Trade Organisation (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement), signatory countries are entitled to set an appropriate level of protection (ALOP) to protect their economy, society, and environment from pests and diseases (see Chapter 2. Biosecurity Systems and International Regulations). The WTO Agreement aims to achieve open and non-discriminatory trade policies, including policies aimed at mitigating biosecurity risks. Although principles of economic efficiency would dictate an assessment of the benefits and costs of risk mitigation measures, this is not a requirement under the SPS Agreement. Rather, the language of the SPS Agreement used to describe the choice and application of ALOP (e.g. Article 5.3; WTO 1995) leads biosecurity agencies to choose measures that reduce risk to negligible levels and to focus on the direct risk-related costs of imports (rather than on foregone trade benefits to domestic consumers).

At present, many methods used by biosecurity agencies to prioritise threats and activities and allocate budgets do not make use of economic principles. Funding allocations based on subjective opinions, historical legacies, the visibility of a threat, or industry pressure do not account for the value for money of projects and are thus economically inefficient. As a perceived improvement, many agencies allocate funding based on risk assessment results or lists of priority species. Although these methods give insight into the relative risks posed by species, they give no insight into the value for money of the activities that could be implemented to manage those risks. Failure by biosecurity agencies to incorporate economic principles wastes taxpayers' money, as implementing unnecessary or ineffective activities does not provide the highest value for the money spent. Budget misallocations can also contribute to increasing risk throughout the biosecurity system as a whole, as underperforming or ineffective programs detract resources from other risk-reducing activities (see Chapter 10. Monitoring, Evaluation, and Reporting).

The basic premise of value for money holds regardless of whether allocation decisions are made to respond to a single threat, across a portfolio of threats, or at different stages of the biosecurity system (namely pre-border, border, or post-border). In an ideal world, a decision maker would consider the costs of prevention and management activities and their effects on reducing damages for all pests and diseases simultaneously. Optimal effort would be identified for each activity, and funds would be allocated to the activities and pests where the value of risk reduction is greatest, subject to a budget constraint (Heikkilä 2011; Moffitt and Osteen 2006).

In practice, it is very difficult for biosecurity agencies to obtain all the data required to compute and select the most economically efficient set of activities across all threats. One of the suggested reasons for the limited uptake of economic principles in biosecurity is the complex nature of biosecurity funding decisions, rather than the simple decision of whether to fund or not (Epanchin-Niell 2017). Policymakers are often faced with large numbers of threats, and each can be associated with a complex range of biosecurity activities pre-border, at the border, and post-border.

For these reasons, resource allocation methods in biosecurity should be practically implementable, even with limited input data. Biosecurity activities are often designed at the early stages of an incursion or risk mitigation planning process, where information about a threat is limited or uncertain (see Chapter 7. Prepare, Respond, and Recover). This chapter has shown that project costs can be broken down into measurable components (e.g. operational, infrastructure, or per-unit costs) and benefits can be estimated using well-established market and non-market evaluation methods and, where necessary, the assistance of an economist. Benefit and cost information compiled for previous projects (e.g. for the purposes of monitoring and evaluation; see Chapter 10. Monitoring, Evaluation, and Reporting) should be collated and used to inform budget allocation. In some cases, using benefit transfer techniques (e.g. from other projects or geographic areas) can be useful; in other cases, structured expert elicitation of potential benefits will be necessary. In some cases, estimating a subset of impacts or benefits (e.g. monetary benefits) might be sufficient (as in the hypothetical example of the Asian green mussel in Box 9.2).

Even when the ecological dynamics of threats and the effects of management activities are uncertain, advances in spread modelling (and associated sensitivity analyses; see Chapter 14. Map) have enabled more reliable valuation and prioritisation in biosecurity (Kompas et al. 2019). Similarly, using structured expert elicitation to gather information from experts (see Chapter 12. Elicit) can fill data gaps and be subject to high standards of scientific enquiry and sensitivity analyses.

When a project mix contains mutually exclusive and independent projects, or when independent projects are expected to show non-constant RTS (Figure 9.5), estimating benefit-cost curves is essential to achieving cost-efficiency. Because diminishing RTS is expected for most biosecurity applications, assuming a generic diminishing returns benefit-cost curve based on sparse data is likely to lead to more efficient prioritisation than assuming constant RTS and using overall BCR to rank independent projects (Figure 9.5). When data are sparse, RTS can also be accounted for by using simple project blocks (Table 9.4). If data are too sparse to make appropriate assumptions or calibrate sensitivity analyses regarding project costs and benefits, the utility of conducting projects with very uncertain costs or benefits should be questioned.

Beyond data availability, another possible explanation for the lack of uptake of economic principles by biosecurity agencies is the perceived lack of practical and readily applicable prioritisation methods. While it may not be possible to develop and apply sophisticated optimisation models to assist in all budget allocations, this chapter has shown that simple prioritisation problems can be solved using pen and paper by following basic economic principles (Figure 9.3 and Table 9.4). In practice, biosecurity agencies could implement BCAs to allocate funding across candidate projects by using simple spreadsheet tools, thereby greatly improving the benefits reaped from taxpayer money. When prioritisation problems are complex and spreadsheet tools are no longer suitable, consultation with appropriately qualified economists (e.g. natural resource or agricultural economists) is advisable. This chapter is intended as a palatable guide for biosecurity practitioners to understand and commission the development of prioritisation tools. The decision tree outlining the suitability of prioritisation methods (Figure 9.5) focuses on the different decision-making contexts faced by a regulator and aims to support communication and consultation with economists.

The lack of application of well-established economics methods in biosecurity constitutes a breakdown in the research uptake process—one with potentially high costs to society. Strong leadership support in favour of cost-efficient resource allocation, basic economics training for biosecurity staff, appointing knowledge brokers to bridge organisational silos, and creating social opportunities for knowledge sharing are strategies that could be employed by biosecurity agencies to shift organisational culture and attitudes (see Chapter 11. Research Uptake). Creating a strong monitoring and evaluation culture (see Chapter 10. Monitoring, Evaluation, and Reporting) may not only contribute to an increased information base on the costs and benefits of past projects, but such an approach may also encourage critical assessment of projects in terms of their value for money.

Many government policies are politically driven rather than based on the best evidence or methods available (Bray, Gray, and Stanton 2020). Government decision making is constrained by past choices, established programs and their funding, and ongoing risk avoidance (Matheson 1998). In Australia, two high-profile reviews have questioned the current allocation of biosecurity budgets (Australian National Audit Office 2021; Inspector-General of Biosecurity 2021). Policymakers may choose to ignore methods that put in question past decisions, or they may disregard resource allocation results that contradict their aspirations or that are unpalatable to vested interest groups. However, there is a strong argument that value for money should be the overarching criterion driving budget allocations when taxpayer dollars are being spent.

Public sector agencies are subject to extreme top-down budgetary pressures. As long as economic principles remain on the periphery of biosecurity decision making, biosecurity agencies will forgo the opportunity to understand (and credibly ask for) the total budget that is required to reduce biosecurity risks to a socially acceptable level (as has been investigated in species conservation (Wintle et al. 2019). Biological threats from pests and diseases are just one of many hazards confronting societies (e.g. climate change, cybersecurity threats, terrorism; World Economic Forum 2022). The high-level decision about how many resources to devote to reducing biological threats compared to other hazards is largely a political decision, which implicitly reflects the relative priority given to this type of hazard (Heikkilä 2011). The costs of managing COVID-19 (in the order of billions of dollars for many economies) and the massive impacts of the disease are a cogent reminder of the potential size of biosecurity impacts if threats are not managed effectively.

IN A NUTSHELL

- Budgets will never be adequate to eliminate or reduce all risks. Because of this, biosecurity agencies must choose which projects to implement to manage threats.
- An activity is cost-efficient if no other use of resources would yield a higher value to the community. When taxpayer dollars are being spent, cost-efficiency (i.e. “value for money”) should be the overarching criterion driving budget allocations.
- Funding allocations based on subjective opinions, historical legacies, industry pressure, or risk assessments do not account for the “value for money” of competing projects and are economically inefficient.

- To prioritise biosecurity activities, regulators should obtain data on the costs of management activities and their potential benefits (avoided damages) and use an appropriate economic method for the problem at hand.
- As biosecurity agencies become more familiar with economics methods, the process of identifying and closing key data gaps can also become more targeted.

REFERENCES

Australian National Audit Office. 2021. Responding to Non-Compliance with Biosecurity Requirements: Department of Agriculture, Water and the Environment.

Boardman, A. E., D. H. Greenberg, A. R. Vining, and D. L. Weimer. 2018. *Cost-Benefit Analysis: Concepts and Practice*. 5th ed. Cambridge: Cambridge University Press.

Bossuyt, J., L. Shaxson, and A. Datta. 2014. Study on the uptake of learning from EuropeAid's strategic evaluations into development policy and practice. Final Report. European Commission.

Bray, J. R., M. C. Gray, and D. I. Stanton. 2020. "Performance Management and Evaluation Meets Culture and Politics: Australia's Experience." *Asia Pacific Journal of Public Administration* 42 (4):290–302. https://doi.org/10.1080/23276665.2020.1808491.

Cacho, O. J., R. M. Wise, S. Hester, and J. Sinden. 2008. "Bioeconomic Modeling for Optimal Control of Weeds in Natural Environments." *Ecological Economics* 65: 559–568.

Chouinard, J. A. 2013. "The Case for Participatory Evaluation in an Era of Accountability." *American Journal of Evaluation* 34 (2):237–253. https://doi.org/10.1177/1098214013478142.

Cook, D., R. Fraser, J. Waage, and M. Thomas. 2011. "Prioritising Biosecurity Investment between Agricultural and Environmental Systems." *Journal für Verbraucherschutz und Lebensmittelsicherheit* 6 (1):3–13. https://doi.org/10.1007/s00003-011-0689-0.

Cook, D. C., G. Long, H. P. Possingham, L. Failing, M. Burgman, R. Gregory, R. Estevez, and T. Walshe. 2012. Potential methods and tools for estimating biosecurity consequences for primary production, amenity, and the environment. Australian Centre of Excellence for Risk Analysis.

Costanza, R., I. Kubiszewski, N. Stoeckl, and T. Kompas. 2021. "Pluralistic Discounting Recognizing Different Capital Contributions: An Example Estimating the Net Present Value of Global Ecosystem Services." *Ecological Economics* 183:106961. https://doi.org/10.1016/j.ecolecon.2021.106961.

Coutts, A, and B. M. Forrest. 2007. "Development and Application of Tools for Incursion Response: Lessons Learned from the Management of the Fouling Pest *Didemnum vexillum*." *Journal of Experimental Marine Biology and Ecology* 342 (1):154–162. https://doi.org/10.1016/j.jembe.2006.10.042.

Craik, W., D. Palmer, and R. Sheldrake. 2017. *Priorities for Australia's Biosecurity System. An Independent Review of the Capacity of the National Biosecurity System and Its Underpinning Intergovernmental Agreement*. Canberra: Department of Agriculture and Water Resources.

Dodd, A. J., N. Ainsworth, C. E. Hauser, M. A. Burgman, and M. A. McCarthy. 2017. "Prioritizing Plant Eradication Targets by Re-Framing the Project Prioritization Protocol (PPP) for Use in Biosecurity Applications." *Biological Invasions*:1–15. https://doi.org/10.1007/s10530-016-1335-7.

Dodd, A., N. Stoeckl, J. B. Baumgartner, and T. Kompas. 2020. *Key Result Summary: Valuing Australia's Biosecurity System, CEBRA Project 170713*. Centre of Excellence for Biosecurity Risk Analysis.

Emerton, L., and G. Howard. 2008. *A Toolkit for the Economic Analysis of Invasive Species*. Nairobi: Global Invasive Species Programme, CABI/IUCN.

Epanchin-Niell, R. S. 2017. "Economics of Invasive Species Policy and Management." *Biological Invasions*:1–22. https://doi.org/10.1007/s10530-017-1406-4.

Epanchin-Niell, R. S., and A. Hastings. 2010. *"Controlling Established Invaders: Integrating Economics and Spread Dynamics to Determine Optimal Management*." 13 (4):528–541. https://doi.org/10.1111/j.1461-0248.2010.01440.x.

Fox, A. M., and D. R. Gordon. 2004. "Criteria for Listing Invasive Plants." *Weed Technology* 18: 1309–1313.

Harrison, M. 2010. Valuing the Future: the Social Discount Rate in Cost-Benefit Analysis. In *Visiting Researcher Paper*. Canberra: Productivity Commission.

Hauser, C. E., and M. A. McCarthy. 2009. "Streamlining 'search and destroy': Cost-Effective Surveillance for Invasive Species Management." *Ecology Letters* 12 (7):683–692. https://doi.org/10.1111/j.1461-0248.2009.01323.x.

Heikkilä, J. 2011. "Economics of Biosecurity Across Levels of Decision-Making: a Review." *Agronomy for Sustainable Development* 31 (1):119. https://doi.org/10.1051/agro/2010003.

Hester, S. M., S. J. Brooks, O. J. Cacho, and F. D. Panetta. 2010. "Applying a Simulation Model to the Management of an Infestation of *Miconia calvescens* in the Wet Tropics of Australia." *Weed Research* 50 (3):269–279. https://doi.org/10.1111/j.1365-3180.2010.00778.x.

Hester, S. M., O. J. Cacho, F. Dane Panetta, and C. E. Hauser. 2013. "Economic Aspects of Post-Border Weed Risk Management." *Diversity and Distributions* 19 (5-6):580–589. https://doi.org/10.1111/ddi.12053.

Hester, S., and J. Mayo. 2021. Improving the Methodology for Rapid Consequence Assessment of Amenity and Environmental Pests. Centre of Excellence for Biosecurity Risk Analysis.

Hulme, P. E. 2009. "Trade, Transport and Trouble: Managing Invasive Species Pathways in an Era of Globalization." *Journal of Applied Ecology* 46 (1):10–18. https://doi.org/10.1111/j.1365-2664.2008.01600.x.

IGB. 2019. *Pest and Disease Interceptions and Incursions in Australia*. Canberra: Inspector-General of Biosecurity. Department of Agriculture and Water Resources.

Inspector-General of Biosecurity. 2021. *Adequacy of Department's Operational Model to Effectively Mitigate Biosecurity Risks in Evolving Risk and Business Environments*. Canberra: Department of Agriculture and Water Resources.

Kim, C. S., D. Lee, G. Schaible, and U. Vasavada. 2007. "Multiregional Invasive Species Management: Theory and an Application to Florida's Exotic Plants." *Journal of Agricultural and Applied Economics* 39 (s1):111–124. https://doi.org/10.1017/S1074070800028984.

Kompas, T., and T. N. Che. 2001. An Economic Assessment of the Potential Costs of Red Imported Fire Ants in Australia. ABARES.

Kompas, T., L. Chu, A. Dodd, and H. T. M. Nguyen. unpub. Misusing Cost-Benefit Analysis. *Centre for Environmental and Economic Research*, University of Melbourne.

Kompas, T., L. Chu, and H. T. M. Nguyen. 2016. "A Practical Optimal Surveillance Policy for Invasive Weeds: An Application to Hawkweed in Australia." *Ecological Economics* 130:156–165. http://doi.org/10.1016/j.ecolecon.2016.07.003.

Kompas, T., L. Chu, P. Van Ha, and D. Spring. 2019. "Budgeting and Portfolio Allocation for Biosecurity Measures." *Australian Journal of Agricultural and Resource Economics*. https://doi.org/10.1111/1467-8489.12305.

Matheson, C. 1998. "Rationality and Decision-Making in Australian Federal Government." *Australian Journal of Political Science* 33 (1):57–72. https://doi.org/10.1080/10361149850723.

Moffitt, L. J., and C. D. Osteen. 2006. "Prioritizing Invasive Species Threats Under Uncertainty." *Agricultural and Resource Economics Review* 35 (1): 41–51.

MPSC. 2018. *Australian Priority Marine Pest List: Process and Outcomes*. Canberra: ABARES. [Report].

Murphy, B., and D. Paini. 2010. CCIMPE Review: UPDATE 2007–2009.

Nordblom, T. L., M. J. Smyth, A. Swirepik, A. W. Sheppard, and D. T. Briese. 2002. "Spatial Economics of Biological Control: Investing in New Releases of Insects for Earlier Limitation of Paterson's Curse in Australia." *Agricultural Economics* 27 (3):403–424. https://doi.org/10.1016/S0169-5150(02)00069-5.

Odom, D. I. S., O. J. Cacho, J. A. Sinden, and G. R. Griffith. 2003. "Policies for the Management of Weeds in Natural Ecosystems: the Case of Scotch Broom (*Cytisus scoparius*, L.) in an Australian National Park." *Ecological Economics* 44: 119–135.

Pannell, D. J., H. T. M. Nguyen, H. L. Chu, T. Kompas, and A. Rogers. 2024. "Benefit-Cost Analysis Decision Criteria: Reconciling Conflicting Advice." *Applied Economics Teaching Resources* 6 (1):13–28. https://doi.org/10.22004/ag.econ.341811.

Productivity Commission. 2013. On Efficiency and Effectiveness: Some Definitions. In *Productivity Commission Staff Research Note*. Canberra: Productivity Commission. [Report].

Regan, T., M. A. McCarthy, P. W. J. Baxter, F. D. Panetta, and H. P. Possingham. 2006. "Optimal Eradication: When to Stop Looking for an Invasive Plant." *Ecology Letters* 9: 759–766.

Robinson, A., M. Chisholm, R. Mudford, and R. Maillardet. 2015. "Ad Hoc Solutions to Estimating Pathway non-Compliance Rates Using Imperfect and Incomplete Information." In *Biosecurity Surveillance: Quantitative Approaches*, edited by F. Jarrad, S. Low-Choy and K. Mengersen, 167–180. CABI International.

Summerson, R., S. Hester, and S. Graham. 2018. *Methodology to Guide Responses to Marine Pest Incursions Under the National Environmental Biosecurity Response Agreement*. Centre of Excellence for Biosecurity Risk Analysis.

Tongue, A. 2020. *Future Department Review: Revitalising the Organisation to Deliver for the Government and Australians*. Canberra: Department of Agriculture, Water and the Environment.

Virtue, J. G. 2007. “Weed risk assessment in South Australia.” 2nd International weed risk assessment workshop., Perth, Australia.

Wintle, B. A., N. C. R. Cadenhead, R. A. Morgain, S. M. Legge, S. A. Bekessy, M. Cantele, H. P. Possingham, J. E. M. Watson, M. Maron, D. A. Keith, S. T. Garnett, J. C. Z. Woinarski, and D. B. Lindenmayer. 2019. “Spending to Save: What Will It Cost to Halt Australia’s Extinction Crisis?” *Conservation Letters* 12 (6):e12682. https://doi.org/10.1111/conl.12682.

World Economic Forum. 2022. Global Risks Report 2022. Geneva: World Economic Forum.

WTO. 1995. “The WTO agreement on the application of Sanitary and Phytosanitary Measures (SPS Agreement).” World Trade Organization, accessed 13 January 2023. https://www.wto.org/english/tratop_e/sps_e/spsagr_e.htm.

Yemshanov, D., R. G. Haight, F. H. Koch, B. Lu, R. Venette, D. B. Lyons, T. Scarr, and K. Ryall. 2015. “Optimal Allocation of Invasive Species Surveillance With the Maximum Expected Coverage Concept.” *Diversity and Distributions* 21 (11):1349–1359. https://doi.org/10.1111/ddi.12358.

Yemshanov, D., R. G. Haight, F. H. Koch, R. C. Venette, T. Swystun, R. E. Fournier, M. Marcotte, Y. Chen, and J. J. Turgeon. 2019. “Optimizing Surveillance Strategies for Early Detection of Invasive Alien Species.” *Ecological Economics* 162:87–99. https://doi.org/10.1016/j.ecolecon.2019.04.030.

Yokomizo, H., H. P. Possingham, M. B. Thomas, and Y. M. Buckley. 2009. “Managing the Impact of Invasive Species: the Value of Knowing the density–Impact Curve.” 19 (2):376–386. https://doi.org/10.1890/08-0442.1.