Incentive-compatible biosecurity policies — a framework for regulatory design

Final Report for CEBRA Project 21C

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Actuarial pricing: Actuarial pricing is how insurers turn uncertain future losses into a premium. It covers expected claims and running costs and pays for the capital that backs the promise to pay. Note that in actuarial science, 'risk' is shorthand for the uncertain financial liability/exposure that needs to be priced.

Actuarial science: is a field that evaluates financial risks in insurance and finance using mathematical, economic and statistical techniques.

Adverse selection: refers to the challenge of assigning agents with varying risk profiles to contracts where insurance premiums are based on the agent's risk rating.

Alignment problems: the differences that occur between how a principal and agent in an organisation would prefer a particular task to be done. Where alignment problems exist, there are potential gains to both parties from improving the incentives of the agent for undertaking the task.

ALOP (Appropriate Level of Protection): Under the *Sanitary and Phytosanitary Measures Agreement*, World Trade Organization members are entitled to maintain a level of protection they consider appropriate to protect life or health within their territory. Australia's ALOP, as defined in the *Biosecurity Act 2015* (Australian Government, 2015), is expressed as providing a high level of sanitary and phytosanitary protection aimed at reducing risk to a very low level, but not to zero.

Approaches to managing biosecurity risks: under a **centralised approach** risk mitigation activities — including pre-border initiatives, border controls, and post-border interventions — are imposed by biosecurity authorities, with management decisions based largely on technical considerations. By contrast, under a **decentralised** system, national biosecurity objectives are implemented through the decisions of risk-creators, who face the full cost of their decisions and actions.

Asymmetric information: occurs when information is unevenly distributed amongst actors in the economy, particularly when one party to a transaction has more or superior information compared to another.

Catastrophe modelling: a technique used to quantify the potential financial impact of risk events that are infrequent, high-cost and for which there is limited historical data.

Complexities (market): the various factors and interactions that make buying and selling in markets more complicated, including policy, transaction, strategic, and timing complexities.

ELOP (Efficient Level of Protection): for biofouling, occurs where value created from transactions between all inbound vessels and the biosecurity authority (the market) is maximised considering all benefits and costs, including biosecurity costs.

Experimental economics: the testing and refining of incentive and information structures on human behaviour via economic experiments undertaken in a controlled environment (e.g., laboratory or field).

Game theory: allows the study of strategic behaviour between two or more agents when they have more than one strategy from which to choose and their choices affect the returns (i.e., payoffs) of another agent in the interaction.

Hidden action problem: also known as moral hazard, occurs when one party in a transaction or contract takes actions that are hidden from, or unobservable by, the other party.

Incentives: inducements for individuals to take actions that they would otherwise not consider. Incentive-compatible policies align the actions of self-interested individuals with a broader policy objective.

Incentive compatibility constraint: A policy is ‘incentive-compatible’ when each participant in their own interest makes decisions that are aligned with the objectives of the policy.

Market: places where buyers and sellers meet to trade goods and services. It is where the price and amount traded are determined; where the basic questions of what should be produced, how it should be produced and for whom, are solved.

Market design: a method for creating rules and processes to organise transactions to achieve a defined outcome.

Market design economics: rather than focusing on traditional economic models (where the equilibrium of supply and demand is the focus), a new field of economics recognises that well-functioning markets depend on detailed rules. Game theory, strategic behaviour, and experimental economics are combined in market design economics to provide insights into efficiently addressing market failure.

Market failure: situations where transactions do not allocate goods and services efficiently. A range of factors can lead to market failure, including public goods, externalities, missing or weak property rights, lack of competition, and transaction complexities.

Missing market problems: occur when a market for a particular good or service doesn’t exist, even though there are potential buyers and sellers to benefit from transactions. Causes include information and incentive problems, high transaction costs, lack of information, or externalities, all of which prevent the market from forming.

Moral hazard: see **hidden action problem.**

Principal-agent problems: occur where a task is delegated by a principal (who accrues the direct benefits of the task) to an agent (who bears the direct time and effort costs).

Public goods: types of goods where use by one person does not prevent access or reduce availability to other people. Those consuming public goods cannot be stopped from accessing them or failing to pay for them. Examples of public goods include ecosystem services, national security, or street lighting.

1. Executive Summary

This report summarises four years of research completed under CEBRA Project 21C '*Incentive-compatible biosecurity policies — a framework for regulatory design'*. The objective of this project is to draw attention to the importance of systematically considering incentives when designing and implementing biosecurity interventions. The project aims to equip biosecurity agency staff with the skills to pinpoint incentive issues in existing/planned interventions and determine strategies for their correction, ultimately supporting more efficient management of pathway risk.

The premise of the project is that while the development of biosecurity interventions relies on deep technical knowledge of the relevant threat, Australia's risk of exposure to many pests and diseases is in part determined by the actions of individuals and organisations involved in import supply chains — i.e., by human behaviour. Since each intervention establishes rules, rights, obligations, and processes that are, essentially, creating incentives for particular behaviours to occur, the human-behaviour aspects of each intervention must be given due attention for interventions to be efficient and effective.

Focusing on the incentive properties of rules is an important, and often neglected, part of designing biosecurity interventions. When the incentive properties of interventions aren't given proper attention, well-intentioned biosecurity interventions can cause counterproductive consequences for the environmental, economic, cultural and societal assets they are aiming to project; human behaviour may actually lead to outcomes that contradict stated biosecurity objectives.

There are two key outputs of the project. The first is a tool for checking and refining incentives in interventions — the *Incentive Diagnostic Tool*. The tool has been tested on several pathways, including biofouling, where problems associated with incentives were detected. The second is a case study that demonstrates how 'incentive-compatibility' can be designed into a biosecurity system based on modern risk management principles. The latter applies the combined skills of actuaries, market design economists and departmental experts in marine biosecurity. The mechanism provides a way forward for efficient and effective management of biofouling risks more generally.

Use of the tool and development of the biofouling case study generated significant new insights into how to fund the biosecurity system sustainably, efficiently and fairly and how to engineer incentive structures needed to encourage risk-creators to truthfully reveal information needed by the biosecurity authority to manage risk. It involves the application of actuarial methods to price biosecurity risk, as well as incorporating incentive and market design theory. This method fundamentally improves the way biosecurity could be managed in the economy.

1.1 Key Findings

1. There will be significant savings to Australian taxpayers if biosecurity interventions are 'incentive-compatible'.

Incentives matter! Incentives inherent in interventions should be checked and refined during the intervention-design stage to avoid costly errors to the Australian economy, environment and community from rules that cause the 'wrong' stakeholder behaviour. CEBRA Project 21C has developed the only known tool that could assist biosecurity decision-makers in this task.

The proof-of-concept *Incentive Diagnostic Tool* provides a methodology for designing interventions that align stakeholder incentives with desired behaviour, while minimising implementation costs.

2. Applying the tool requires an interdisciplinary team.

Applying the tool typically involves an interdisciplinary team — pathway experts; operations and regulatory staff; market design economists; actuaries; and industry stakeholders. While pathway experts should be able to source the information required to *diagnose* whether incentive problems exist, a market design economist will likely be required for the *design* of the incentive-compatible policy itself. Systematically capturing the tool's use cases will reduce the time taken in the design phase and may reduce the reliance on specialised market design economists.

3. The application of actuarial science in the biofouling domain could fundamentally change biosecurity risk management.

The emerging capability to price biosecurity risk through the application of actuarial science has been demonstrated for the biofouling pathway, but it could be applied more broadly. Monetising biosecurity risk fundamentally changes the way that biosecurity could be managed in the economy, bringing efficiency, efficacy and transparency advantages compared with a centralised approach to biosecurity management.

4. Implications for biosecurity costs of an insurance approach.

A case study approach was used to explore the impact of a biosecurity risk insurance model on biosecurity compliance costs. For one cohort of vessels — those that invest low-effort in biofouling mitigation actions — a 57% reduction in overall biosecurity costs (inspection and compliance costs) was estimated. These savings partly arise from beneficial behaviour change by vessel operators in response to incentives, including the price of biosecurity risk, created by a market for biosecurity risk insurance. The most important benefit arises, however, from the scope to implement a national biosecurity objective that has an economic efficiency focus — as opposed to the current approach.

1.2 Recommendations

To take advantage of the outputs and outcomes of CEBRA Project 21C we recommend that:

1. **Further testing and refining of the Incentive Diagnostic Tool take place, and results from its application to pathways be systematically captured.**

To progress the proof-of-concept tool there is a need to further test it with a range of different 'types' of pathways. While use of the tool to solve the biofouling-type of incentive problems could occur relatively quickly, there is a need to test the tool on a range of other pathway problems. While investment in the skills of market design economists will lead to a relatively efficient policy solution, there is scope for a light-touch use of the tool where staff focus solely on the diagnostic aspect of the tool, however a relatively less efficient solution is likely.

2. The Incentive Diagnostic Tool be embedded within the department's policy design process.

Although little effort has been made to collect empirical evidence of the extent of incentive problems in biosecurity, many biosecurity problems appear to arise from decisions made by stakeholders. Two responses should be considered by the department: i) a systematic assessment of the extent to which human behaviour has contributed to the introduction and spread of exotic pests and diseases in the past; and ii) depending on the finding of i), a systematic approach to the application of the tool, including its embedding and dissemination within the department, and subsequent involvement by incentive/market design experts to design incentive structures needed to mitigate the incidence and impact of human behaviour on biosecurity outcomes.

3. That investment be made into applying actuarial approaches to biosecurity risk management more broadly.

Actuarial pricing could be introduced to biosecurity risk management as either a formal market for biosecurity risk insurance or as an actuarial levy on risk-creators (higher risk = higher levy/premium), leading to significant efficiency gains. Significant progress has been made through the CEBRA 21C project in both the actuarial methodologies needed to price biosecurity risk and the application of these principles to biofouling (one domain of biosecurity). Further investment will be needed to apply actuarial methods to all classes of biosecurity risk faced by Australia including from imported goods, plants and animals, and inbound passengers. Given the novelty of the actuarial approach, it will be crucially important to gain legal advice with respect to its status under WTO rules.

4. Designed mechanisms that are developed using the Incentive Diagnostic Tool should be tested in an economics laboratory.

Laboratory testing of policies should be supported. Testing these mechanisms in the safe confines of an economics laboratory will produce estimates of the economic efficiency and efficacy advantages suggested by economic theory, and increase familiarity with the mechanism.

2. Introduction

The Australian Government Department of Agriculture, Fisheries and Forestry (the department) routinely establishes interventions to influence the behaviour of import-supply-chain participants whose actions impact on biosecurity outcomes. These interventions include regulations and inspection regimes, delegation of biosecurity functions to third parties, reputational capital etc. Each intervention establishes rules, rights, obligations, and processes that are, essentially, creating incentives for particular behaviours to occur. Ideally, the incentives created by the intervention should result in compliance by biosecurity stakeholders. An intervention is *incentive-compatible* when it leads decision-makers to "do the right thing" from a biosecurity management perspective.

Focusing on the incentive properties of rules is an important, but neglected, part of designing biosecurity interventions. When the incentives are not given due attention, there can be counterproductive consequences including biosecurity outcomes that conflict with intended biosecurity objectives or result in high-cost interventions. These outcomes can be avoided by checking the incentive properties of interventions pre-roll out and adjusting them as necessary. To date, staff have not had the capacity or capability to carry out this checking.

CEBRA Project 21C focuses on the incentives inherent in biosecurity policies and provides a tool for their checking and refining — the *Incentive Diagnostic Tool* (the tool). The tool has been tested on several pathways, including biofouling, where problems associated with incentives were detected. An 'incentive-compatible' biosecurity mechanism for biofouling was developed, using the combined skills of actuaries, market design economists and departmental experts in marine biosecurity. The mechanism provides a way forward for efficient and effective management of biofouling risks.

Given its focus on incentives, this project is consistent with the recent IGB report into the department's operational model (Inspector-General of Biosecurity, 2021), which discussed the need to explicitly incorporate incentives into biosecurity policy. This was specifically discussed in terms of: shared responsibility and co-regulation (Chapter 3); and understanding behavioural drivers (Chapter 4):

> *"This incentivisation approach should include finding ways to achieve overall biosecurity (and cost) benefits by implementing innovative strategies that will achieve more compliant behaviour and impactful disincentives for noncompliant behaviour"* (p48).

A significant outcome of CEBRA Project 21C is knowledge about how to sustainably, efficiently and fairly fund the biosecurity system. It involves the application of actuarial methods to price biosecurity risk. This method fundamentally improves the way biosecurity could be managed in the economy. Interventions incorporating actuarial principles have economic efficiency, efficacy and transparency advantages compared with the current centralised approach to biosecurity management, in which decisions are currently made based on information held by the biosecurity authority without consideration of the costs imposed in vessel operators. By not taking these costs into account, decisions about the level and type of biosecurity interventions needed, cannot lead to an efficient outcome.

2.1 Objectives

The overarching objective of this project is to create a way for departmental staff to explicitly consider incentives when designing interventions. The effectiveness and efficiency of departmental biosecurity regulations will be significantly improved if incentives are explicitly considered in their design. This improvement is demonstrated via case studies where incentive-compatible policies are the focus.

2.2 Methodology

Designing biosecurity regulations with incentive properties that lead to the desired behaviour of individuals and organisations involves the integration of knowledge about the behaviour of pests and diseases (epidemiology) with knowledge about how humans respond to incentives (economics — incentive theory). There are few precedents, however, for this type of analysis in biosecurity, and because of the varied pathways, products and consequences of regulations, correcting and/or creating incentive-compatible policies is not a straightforward process.

The department is an acknowledged world leader in the application of science to pest and disease control. It is now in a position to improve its processes for implementing biosecurity interventions that also incorporate incentive structures (i.e., incentive compatibility) into biosecurity responses. This initiative draws on past departmental research in this area:

- CEBRA's 'Carrots and Sticks' series of projects (2013–2019; Rossiter et al., 2016, 2018, 2019);
- the 'Competent Authority' project (2017–2019; Campbell et al., 2021); and
- investigations into the creation of markets for biosecurity risk insurance[1] (2019; Stoneham et al., 2021).

This initial research has created a lot of interest and promise, but the tools and techniques needed to design and implement efficient and effective incentive-compatible regulation within the biosecurity domain of the economy need to be further developed so that they become business as usual and applied systematically across the sector.

This multi-year project will use a mix of economic theory and case studies in combination with the department's scientific knowledge to deliver and demonstrate a framework for the development and roll-out of incentive-compatible biosecurity regulation.

2.3 Report Structure

This report summarises four years of research completed in CEBRA 21C, leaving technical details for a series of Appendices. The report is structured as follows:

- Main report – summarises the Incentive Diagnostic Tool (Section 3) and its application to biofouling (Section 4);
- Appendix A – contains the tool's Manual, with an example application to a hypothetical animal import pathway;
- Appendix B – contains the tool's template;

[1] This Department of Agriculture, Water and Environment (now DAFF)-funded project was also supported by NSW DPI and Biosecurity QLD

- Appendix C – provides a partial application of the tool (the diagnostic phase) to ballast water;
- Appendix D – contains technical details of the biofouling case study (the Milestone 11 report for 21C: *A Biofouling Risk Insurance Mechanism*);
- Appendix E – contains the actuarial methodology associated with the case study (the Milestone 8 report for 21C: *Draft Methodology for Identifying Vulnerabilities*);
- Appendix F – presents the results from applying the actuarial methodology (the Milestone 10 report for 21C: *Completion of Actuarial Work on the Designed Mechanism*); and
- Appendix G – sets out the payoff matrix for vessel-entry strategies associated with the case study.

For consistency, page numbers run sequentially throughout the entire document.

3. The Incentive Diagnostic Tool

A proof-of-concept 'Incentive-Diagnostic Tool' (the tool) has been developed to create a systematic framework for departmental staff to incorporate incentives into intervention design. The tool is for checking the incentive properties of biosecurity interventions and for refining or developing interventions as necessary.

The tool consists of a manual (Appendix A) and a stand-alone-template for ease of use (Appendix B). The manual includes an example to assist non-economists use the tool, however in some cases the expertise of a market-design expert may be required to assist with the tool's full application.

The tool provides a rigorous process for designing biosecurity interventions that will change human behaviour in a way that avoids unintended negative consequences. Users are taken through a series of steps to identify which intervention is "best" for a given pathway — i.e., the intervention which achieves the desired reduction in biosecurity risk at the lowest cost. The decision-making processes underpinning the tool are based on a well-established set of ideas from the economics discipline.

There are two uses of the tool:

1. to create a new incentive-compatible biosecurity intervention, see Figure 1 and the summary in 3.1; and
2. to check and refine the incentive properties of an existing intervention, see Figure 2 and the summary in 3.2.

The tool includes:

- a step-by-step diagnostic and economic framing component; and
- a design component.

The **diagnostic and economic framing component** (the diagnostic component) is essential for both uses of the tool, i.e., whether the user is checking an existing intervention or developing a new intervention. The step-by-step guide enables biosecurity agency staff to systematically understand the incentives faced by relevant decision-makers who are subject to a biosecurity intervention. It does this through a sequence of questions, the answers to which can be combined to understand how individuals make decisions that influence biosecurity outcomes and then how existing intervention parameters may be adjusted to induce beneficial changes in behaviour.

Depending on the complexity of the incentive problem identified, the **design component** either refines the existing intervention or identifies the type of mechanism — and the specialised economic-design skills required — to deliver more efficient and effective biosecurity outcomes.

The tool applies economic concepts, typically used by economists with training in market/mechanism design. A hypothetical animals pathway is used as an example to assist non-economists with use of the tool. In some instances, the complex nature of behaviours on a pathway may require a combination of specialist pathway knowledge and market/mechanism design expertise to appropriately design an intervention with the desired incentive properties.

3.1 Use case 1 — Create incentive-compatible biosecurity interventions

The process for using the tool to design incentive-compatible interventions, and to select and implement the best of these, is shown in Figure 1. The 'best' intervention will be the set of rules, processes, technology and incentives that achieve the stated objective at the lowest cost. References to the manual are given in bold. More details can be found in tool's Manual (Appendix A).

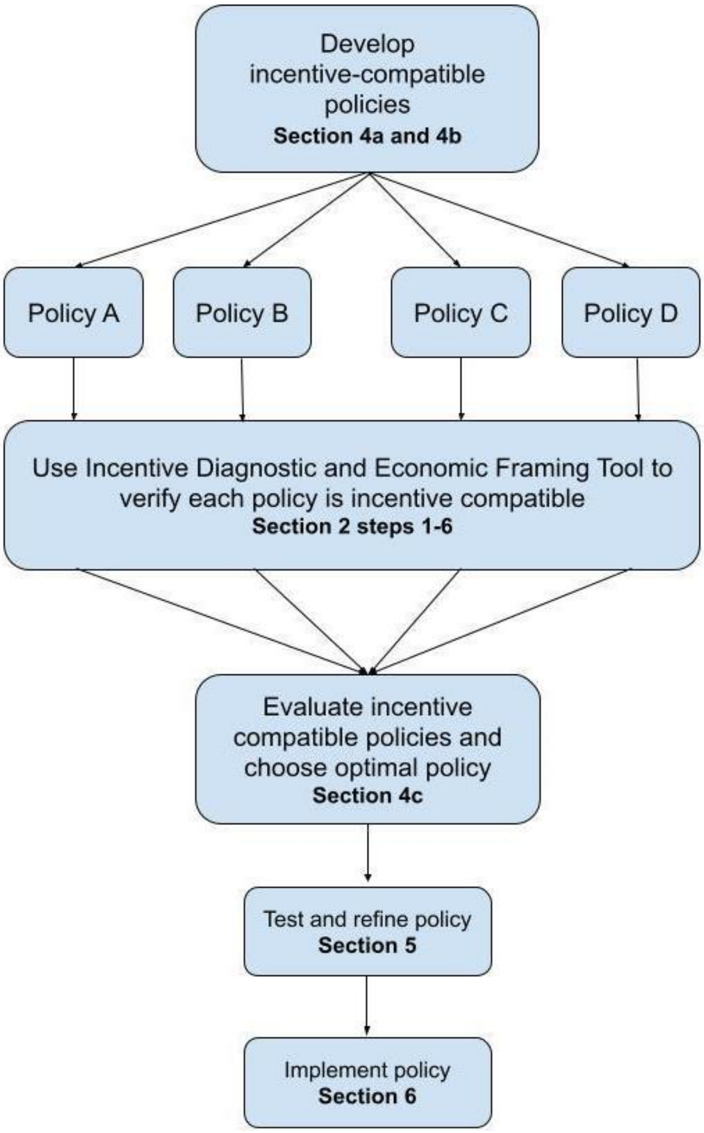


Figure 1. The process for creating the 'best' interventions for a specific biosecurity pathway, and the sections of the Manual in which each is discussed (See Manual, Appendix A).

3.2 Use case 2 — checking and refining the incentive properties of an existing intervention

When behaviour on a pathway appears not to be that which was intended by the intervention, the incentive properties of the intervention can be checked. If an incentive issue is identified (rather than simply confusion, which can be remedied by educational materials), the intervention can be refined to improve behaviour. Refining an intervention may be preferable to completely redesigning it, because fewer departmental resources may be required to attain a satisfactory outcome. Refinement may be achieved through adjusting how some elements of the intervention are implemented, for example: the frequency of inspections; the types of intervention responses to identifying potential non-compliance and/or the use of information in the intervention.

The process for using the tool to check and refine the incentives of an existing intervention is shown in Figure 2. References to the manual are given in bold. More details can be found in Appendix A.

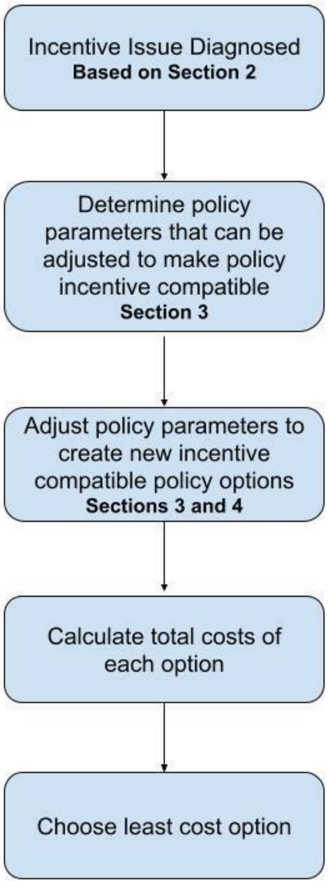


Figure 2. The process for refining interventions for a specific biosecurity pathway, and the sections of the Manual in which each is discussed.

3.3 Resource requirements for tool use

The tool may be used via a 'light touch' application, or applied fully with the likely need of a wider set of experts. The former involves departmental staff moving through the step-by-step diagnostic component (Steps 1-6) at their own pace, leading to a decision about inherent incentives, and whether further support (via full application of the tool) might be required.

Fully applying the tool typically involves an interdisciplinary team — departmental pathway experts, operations staff, industry stakeholders, staff from the Office of the Chief Regulatory Officer (OCR); market design economists; and in some cases, actuaries. Full application of the tool, with the use of market-design expertise in the diagnostic and design phases of the tool, typically occurs as follows:

1. the team initially meets to discuss the tool and the pathway (1-2 hours);
2. regulatory policy officers, pathway managers and operations staff would gather data and information to answer the tool's questions (diagnostic component, steps 1-6) as best they can, and form a conclusion about incentive-compatibility (3 days);
3. where incentive issues are identified, a follow-up session between pathway managers and market design economists would review the information gathered and discuss initial policy solutions (2-hours);
4. economists use the design component to develop a conceptual incentive-compatible solution based on the type of problem, and whether an existing solution can be modified (5 hours);
5. a team meeting is held to discuss the preliminary solution (2 hours);
6. the solution intervention is refined and detailed (1-3 weeks depending on available scientific research and existing solutions);
7. the solution intervention is tested (in an economics laboratory) and refined (6 months with experiments, 1-3 weeks without experiments); and
8. the incentive-compatible intervention is implemented through a staged roll-out process, with evaluation and further adjustment as necessary.

The time required to complete the diagnostic component (step 2) would depend on the problem and the experience of the pathway manager. The remaining steps — designing, refining, and testing the solution and phased rollout — may take several months depending on whether existing incentive-compatible solutions can be modified.

For the light-touch application:

1. regulatory policy officers, pathway managers and operations staff would gather data and information to answer the tool's diagnostic questions as best they can, and form a conclusion about incentive-compatibility (3 days); and
2. where incentive issues are identified, pathway managers would adjust the policy and repeat step 1 until incentive compatibility is reached (1-3 days).
3. The incentive-compatible intervention is implemented through a phased roll-out process with evaluation and further adjustment as necessary.

3.4 Refining and Testing the Incentive Diagnostic Tool

The tool was refined using a hypothetical animals pathway, to avoid potential sensitivities associated with analysing a current operational pathway. On the hypothetical animals pathway, conditions around the importation into Australia of the animals are primarily focused on virus risk mitigation. The tool was subsequently refined using the existing ballast water pathway.

The hypothetical pathway is used in the Manual to assist staff to complete Steps 1–6 of the tool's diagnostic component. In the context of that pathway, analysis of answers highlights that there are incentive problems on the pathway — many hypoanimals customers are willing to pay a premium to have their animals bypass biosecurity protocols and to arrive more quickly in Australia. As such, there is a large potential benefit to importers from bypassing entry protocols to service the demands of these customers. Exporters and certifiers reside outside of Australia, making them difficult to monitor and penalise.

A conceptual solution for the hypoanimals example was developed with the use of expertise from market-design economists. In the solution, importers were identified as a potential group who could be influenced to encourage compliance with Australian biosecurity regulations. A licensing strategy is suggested where Australian-based importers bid for licenses to import hypoanimals. Successful bidders are granted exclusive rights to import hypoanimals but are required to lodge a bond that can be forfeited if they found to be circumventing the laws.

Building on this initial example, additional testing of the tool took place via application of the tool to the ballast water pathway, where there was anecdotal evidence of non-compliance with Australia's ballast-water requirements (see Appendix C). A ballast-water pathway expert was asked to complete Steps 1-6 of the tool's diagnostic component and give feedback on their experience answering questions. The pathway expert was able to answer most of the questions and develop a conclusion about the likelihood of non-compliance: that there is a low likelihood that vessels will be caught avoiding ballast water rules, and because of this, there is likely an incentive problem in current ballast water policy implementation. Application of the tool beyond the diagnostic component was not undertaken for ballast water.

4. Case Study: an incentive-compatible biofouling mechanism

Biofouling was selected as a case study to show the outcome of applying the *design* component of the Incentive Diagnostic Tool. Biofouling was selected because the policy intervention and implementation process for this pathway is currently being developed, both in Australia and internationally. The case study details the fine-scale economic architecture (i.e., rules, processes and incentive structures) needed to implement an efficient and efficacious insurance-/actuarial levy-based approach to biosecurity.

The design process draws on the diagnostic and economic framing approach embodied in the tool (Section 2 of the tool's Manual). Because of the nascent status of biofouling, this case study focuses on identifying the mechanism needed to implement biosecurity objectives, rather than on improving the performance of existing policy/regulatory interventions. The resulting mechanism incorporates rules and processes (including incentive structures) needed to achieve outcomes that are efficacious and efficient, with its funding model designed to reduce reliance on general taxation and mitigate associated deadweight loss. The mechanism is summarised in this section, and described in full in Appendices D-G.

4.1 Introduction

Non-indigenous marine species (NIMS) can cause economic, environmental, human health and amenity losses if transmitted to Australian ports on inbound vessels. Williams (1978) identified 20 species which have been introduced to Australian waters (see also Pollard and Hutchings, 1990) typically through biofouling of vessel hulls and ballast water discharge (Arndt et al., 2021). These and other biosecurity threats are currently managed by the biosecurity authority through a centralised approach, where activities including pre-border initiatives (e.g., surveillance), border controls (e.g., regulation and inspection of imported goods/inbound vessels), and post-border interventions (e.g., funded control and eradication programs) are imposed by biosecurity experts within a government agency. Management decisions are based largely on technical considerations.

The emerging capability to actuarially price biosecurity risk (Appendix E) and its demonstrated application to biofouling (Appendix F), fundamentally changes the way that biosecurity could be managed in the economy. This capability, if applied systematically, enables markets for biosecurity risk to be created in which prices act as an incentive for risk-creators to reduce Australia's exposure to biosecurity risk. It would also establish a sustainable pool of funds available to manage and respond to biosecurity threats as they occur.

Actuarial pricing of biosecurity risk can be implemented as either a *market for biosecurity risk insurance contracts* or as an *actuarial levy on risk-creators*. These mechanisms are used interchangeably in this report. The levy rate in the actuarial levy approach would be set at the same rate as the risk insurance premium in an insurance approach. They require the same supporting structures and can only be successfully implemented if incentive problems common to all risk markets can be resolved.

The broad objective of this report is to identify the economic architecture of a market for biosecurity risk insurance contracts/actuarial levy mechanism needed to implement actuarial pricing of biofouling risk. It applies market design concepts and incentive theory (as set out in Section 3 and Appendix A) to establish the rules and processes needed to organise the way inbound vessels would engage with the biosecurity authority to manage biosecurity risk through a decentralised approach to biosecurity.

A brief summary of the foundation ideas, on which the report is based, is provided in the following section, and Section 4.3 gives a brief account of the incentive-compatible mechanism. Full details of the mechanism are given in Appendices D-G.

4.2 Diagnosis and Economic Framing

Exotic pests and diseases introduce risk into the Australian economy. In the marine context, each inbound vessel exposes Australia to possible economic, environmental, health and welfare losses if NIMS are inadvertently introduced. The role of Australia's biosecurity system is to reduce these risks and respond to unacceptable biosecurity risks as they arise and by implementing an Acceptable Level of Protection (ALOP), which, for Australia is to achieve a 'very low' level of biosecurity risk. This objective is currently implemented through a centralised planning approach involving regulation of risk-creators supported by interventions including border inspection, science, surveillance, and investments in preparedness and response capabilities where incursions are detected. In this approach to biosecurity risk management, decisions about the level of effort and allocation of resources are made by biosecurity experts based largely on technical considerations.

Biofouling can be considered a domain of the economy in which markets for risk management products are missing. From a diagnostic perspective, the market for risk management products (such as insurance) are missing in this domain of the economy because of the difficulty, or even impossibility, of attributing financial losses arising from pest or disease incursions to those responsible for creating these risks. Importantly, Stoneham et al. (2021) found biosecurity risks to be insurable. In this context, markets for biosecurity risk insurance products have not emerged or been needed because individual vessel operators cannot be held accountable for the financial, economic, or human welfare losses they cause and therefore have no need to insure against these losses. Consistent with other classes of risk, the first-best policy response to this diagnosis of market failure (see Stoneham et al. 2021) is to create a market for biofouling risk insurance. Three components would be required to implement this approach to biosecurity: i) develop a capability to price/monetise biosecurity risk, ii) design the market needed to transact biosecurity risk insurance contracts, and iii) introduce legislation needed for compulsory participation by all risk-creators. A summary of these components is provided in the following sections.

4.2.1 Actuarial pricing of biosecurity risk

Research completed under CEBRA Project 21C, included engagement of actuaries to develop a methodology for pricing biosecurity risk, and an application to biosecurity risk in the biofouling domain. A methodology for actuarial pricing of biosecurity risk is described by Zhou et. al. (2023; Appendix E). This methodology is based on three components: i) *expected annual losses* from biosecurity incursions; ii) the *risk load* imposed to individual risk-creators; and iii) the *expense load,* including administration, monitoring and response costs, incurred to manage biosecurity risk.

The structure of the actuarial model for biosecurity risk insurance/actuarial levy was based on catastrophe modelling developed for risk events that are infrequent, high-cost and for which there is limited historical data (Grossi and Kunreuther, 2005; Mitchell-Wallace et al., 2017). This methodology was applied to biofouling by Zhou et al. (2025; Appendix F) using a mix of historical data (e.g., vessel arrivals at individual ports, movement history etc.) and synthetic data developed from a survey of scientists[2] to determine the relative likelihood of different incursion scenarios and the likelihood that NIMS introduced would require eradication or containment. Expert opinion was also used to build a model to estimate costs associated with a given incursion based on the probability of choosing eradicating or containment. A statistical model was then developed to combine the frequency model of NIMS incursions with individual scenario cost models to compute estimates of the aggregate cost of biofouling actuarial levies.

To determine the actuarial levy for individual vessels, vessel-specific risk ratings were identified from a range of scientific papers and expert opinion. Contributing risk factors include the age of anti-fouling coating, water temperature and salinity differentials between the destination and departure port, and the berthing duration of the vessel at the port. Actuarial levies defined at the individual voyage level were calculated by disaggregating the overall anticipated insurance costs according to the risk rating of each vessel.

Collectively, these methods were applied to create a statistical model from which the mean and standard deviation of the expected losses were derived. The insurance premium was then calculated as the expected cost of containment/eradication plus biosecurity authority costs and a margin (related to the standard deviation of costs) to cover the risk. The same method would be applied to determine actuarial levies on inbound vessels.

Table 1 reports indicative biofouling actuarial levy rates across the distribution of risk ratings. The six columns in Table 1 represent six simulated vessels with distinct risk profiles. The 'Min' column corresponds to the vessel that paid the lowest premium among all simulated vessels, indicating the lowest biofouling risk. The other five columns represent an increasing biofouling risk, corresponding to the 25th percentile, median, mean, 75th percentile, and maximum premiums, respectively.

These premia in Table 1 include biosecurity administration costs (estimated at $1,354[3] per arrival for commercial vessels) assuming a risk load of 3% of the standard deviation of annual loss[4]. An important feature of these premia is that a significant proportion (96%) reflects uncertainty arising from assumptions in the actuarial model with the remaining 4% reflecting expected losses arising from response costs (the risk component of premiums). As shown in Table 1, premiums/levies increase with a higher risk load. For example, the median premium would increase from $2,618/vessel with a 3% risk load to $3023.5 with a 4% risk loading. The total premium paid by all vessels based on a 3% risk load is sufficient to cover response costs 90.1% of the time given that an incursion has occurred. To achieve a 95% chance of covering response costs, the median total premium per vessel would need to increase to $3,567 (data not shown) — the additional increase helps cover some scenarios with significant costs, i.e., it is kept in reserve. The fact that most of the premium is allocated to risk load suggests our pricing

[2] University of Melbourne Human Ethics ID: 2023-27400-42497-3

[3] Obtained from Biosecurity Cost Recovery Arrangement, Cost Recovery Implementation Statement 2023-2024 https://www.agriculture.gov.au/sites/default/files/documents/biosecurity-cost-recovery-implementation-statement-2023-24.pdf

[4] This assumption is subject to revision.

is primarily structured to protect against rare but high-impact events, rather than merely covering the average cost of a biofouling incident.

In determining the appropriate risk load, it is worth noting that in standard insurance practice companies could be required to hold capital sufficient to cover losses up to the 99.5th percentile[5] of risk. This means they must be prepared for very extreme scenarios, and the premiums they charge include a risk load that reflects the need to cover these potential losses. However, in a government-sponsored biofouling insurance scheme, the government is not bound by these strict capital requirements. Instead, the government can use its broader fiscal resources to cover losses if a worst-case scenario occurs. This flexibility means that the risk load — and hence the premium — can be tailored based on the government's overall risk appetite. However, if the risk load is set too high, the premium could discourage trade by making insurance prohibitively expensive. It's essential to balance fiscal prudence with keeping costs competitive.

Table 1. Premiums for individual inbound vessels^

Risk rating	Min (low-risk)	1st Quarter	Median	Mean	3rd Quarter	Max. (high-risk)
Premium (3% risk loading)	$313.2	$879.6	$1,264.7	$1,180.8	$1,436.2	$2,102.5
Premium (4% risk loading)	$ 416.5	$1,164.5	$1,669.5	$1,558.3	$1,893.5	$2,759.0
Administration costs	$1,354	$1,354	$1,354	$1,354	$1,354	$1,354
Total premium (3%)	$1,667.2	$2,233.6	$2,618.7	$2,534.8	$2,790.2	$3,456.5
Total premium 4%)	$1,770.5	$2,518.5	$3,023.5	$2,912.3	$3,247.5	$4,113.0

^Note that 'Premium' includes expected costs and risk loading, while 'Total premium' also includes Administration costs

Given the assumption that an incursion is expected on average every 5 years across Australia, approximately 80% of years would be event-free. When considering only the vessel arrivals at the six ports as assumed by the model, about 95% of years would be event-free. Combined, the event-free years and the years where incursions occur but the premium is sufficient to cover response costs account for approximately 99.5% of all years.

In years without any events, the premium can be saved as a reserve. In the insurance industry, such reserves are typically invested. This buffer can then be used in years when a major event causes costs that exceed the annual premium. Note that the response cost for those years with a major event can be very large. Essentially, we need to save to ensure that, when severe events occur, there is sufficient funding available to cover the excess costs.

In conventional insurance, a Bonus–Malus (experience-rating) system is often adopted to use an insured party's loss experience to inform future pricing. This system adjusts premiums over time according to verified performance, granting a bonus (discount) for good performance and a malus (surcharge) for poor performance. In the biofouling context, reliable attribution of an

[5] This approach is common in the financial industry; for example, under the Solvency II framework in Europe, insurers must maintain such capital buffers. In Australia, the Australian Prudential Regulation Authority (APRA) enforces similar capital requirements for insurers.

incursion to an individual vessel is often infeasible due to detection lags, multiple potential sources, and environmental dispersion. Consequently, a traditional, loss-attributed Bonus–Malus cannot be operated in the usual way because the core input, credible vessel-specific loss experience, is not available at the required standard.

Instead, the Bonus–Malus would operate ex-post and be anchored to verifiable performance indicators such as audited inspection outcomes on arrival (e.g., graded scores and deficiency counts), timely rectification of deficiencies, adherence to reporting and documentation requirements, and a clean-arrivals ratio measured over a period. Adjustments would follow transparent earning/decay rules: bonuses accrue with consecutive clean arrivals; maluses step down after sustained compliance, subject to published caps and floors for predictability. When premiums rise, some operators may find calls to Australian ports uneconomical and re-route elsewhere. To formalise that deterrent, the regulator could publish a maximum premium loading (e.g., three times the base premium); any quote above that level is deemed "uninsurable," and entry is refused. Regulators also have the power to refuse entry on other grounds — such as inspection failures or repeated incursions — even if insurance is technically available, but that is a separate lever and not simply a by-product of higher premiums.

This adapted design preserves the incentive properties of Bonus–Malus while remaining administratively workable in a regime where incident attribution is not possible. The mechanism is presented as a policy option and is not implemented in this report.

4.2.2 Structure of a market for a biofouling actuarial levy mechanism

Markets define the rules and processes that govern the way buyers and sellers interact to execute transactions. In the current context, the item/service being transacted could be either a *biosecurity risk insurance contract* or an *actuarial levy* imposed on risk-creators (e.g., inbound vessels). Both rely on the application of actuarial methods to determine insurance premiums/levy rates and resolution of specific information and incentive problems that would otherwise impede the efficiency, efficacy and financial sustainability of the proposed mechanism. The structure of the market/mechanism needed to transact these items is identical and the term *biosecurity risk actuarial levy* is used in the following discussion.

The broad market structure needed to implement a biosecurity risk actuarial levy can be observed from markets that have emerged in other domains of insurance. In these markets, variations in the fine-scale rules and processes are observed because of the: characteristics of different classes of risk (influencing the *information space* of the market); and differences in the way risk-creators and the insurer interact to execute transactions (referred to as the *adverse selection* and *moral hazard* problems). The rules and processes needed to design these aspects of the market for biosecurity risk insurance are summarised in the following sections, and described in more detail in Appendix D.

4.2.2.1 Information space

Unlike most markets where price is determined through competition between buyers and sellers, markets for insurance primarily rely on the seller (e.g., the insurance business) applying actuarial methods (discussed above) to determine prices. As shown in Table 1, prices vary according to the level of biosecurity risk exposure relevant to each inbound vessel in the biofouling instance. In this type of market, information about the risk status of those seeking insurance must be revealed so that the relevant price can be determined. In the biosecurity domain, biosecurity risk posed by inbound vessels varies according to a range of vessel design, operation, provenance and environmental factors. A systematic process for revealing information about individual vessel risk will be an important feature of this market. A vessel's Biofouling Management Plan (BMP) is identified in Appendix D as a potential way of creating the *information space* in a market for biosecurity risk insurance. The role of a BMP in this context, would be to specify the information needed, the metrics used to measure each variable, and the process by which information needed to determine the risk rating of each inbound vessel is revealed.

The variables that define the information space in a market for biosecurity risk insurance for inbound vessels are reported in Table 2 — these are defined by the actuarial model. In this context, BMPs would need to be designed to record, report and verify the vessel specific information identified by the actuarial model so that a risk rating can be determined for each vessel. This information would need to be revealed before vessels enter Australian waters as part of the information architecture of the market.

One limitation is that our current pricing assumes that the same number and mix of vessels will continue arriving at Australian ports, and that their biofouling profiles will remain consistent with historical observations. It does not account for potential changes in vessel behaviour, and consequently, changes in the distribution of total annual loss that may arise in response to the policy.

Table 2. Biosecurity risk rating proforma for inbound vessels

Vessel information	Explanation
1. Type of vessel	Class of vessel entering Australian port
2. Type of port	Degree of enclosedness
3. Temperature	Absolute difference in mean temperature between origin and destination port
4. Salinity	Absolute difference in mean water salinity between origin and destination port
5. Duration	Length of stay in port
6. AFC vintage	Age of anti-fouling coating (AFC)
7. Vessel speed	Average speed of vessel – related to vessel type

Behavioural change is a complex issue, and pricing assumptions should be updated once behavioural responses to the policy are better understood.

4.2.2.2 Adverse selection and moral hazard

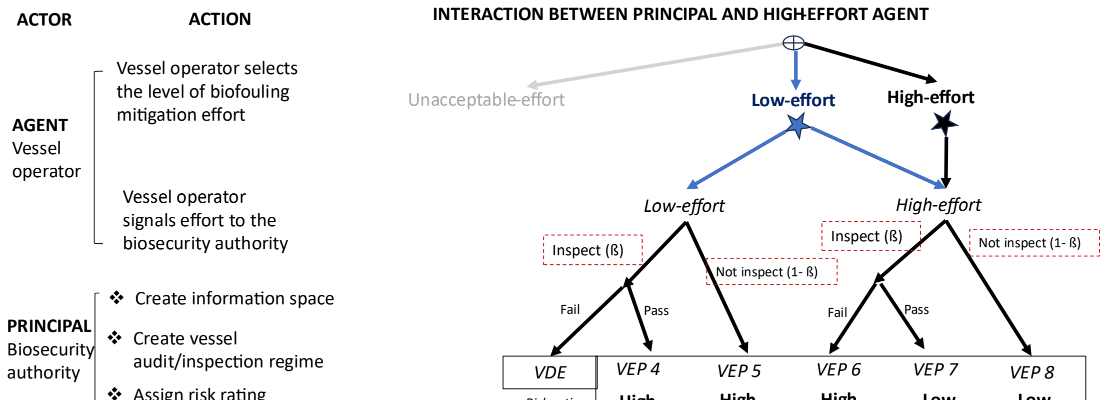
The second important function for the market/mechanism in which biosecurity risk insurance levies are transacted is to resolve/mitigate adverse selection and moral hazard problems. In a biofouling context, *adverse selection* refers to the problem of allocating vessel operators, with different risk profiles, to levy rates that reflect their risk rating. *Moral hazard* occurs when the behaviour of the insured party changes because they take out insurance. Stoneham et al. (2021) argued that while there are opportunities for moral hazard (i.e., deliberate release of exotic pests in Australia), there is no incentive for risk-creators to engage in such activities.

Appendix D applies the economic principles and methodology identified in the tool's manual to identify the rules and processes needed to address the adverse selection problem. It frames the interaction between the biosecurity authority (the insurer/principal) and inbound heterogeneous vessel operators as nodes (decision points of vessel operators) and branches, where a sequence of branches represents a vessel entry pathway (VEP)[6] strategy that could be adopted by each vessel operator. VEPs effectively define the range of strategies that vessel operators could adopt to interact with the biosecurity authority. Each VEP leads to an expected financial payoff (positive or negative) to the vessel operator and an expected biosecurity outcome. Figure 3 illustrates a component of the network of decision nodes, branches and VEPs that apply to vessels investing low effort in biosecurity risk mitigation.

Each VEP involves a series of:

- *decisions* by vessel operators with respect to the signal (e.g., about the level of biosecurity effort invested – see Figure 3);
- *interventions* by the biosecurity authority (e.g., the frequency and type of vessel testing); and
- consequence for vessel operators defined by a *payoff matrix*.

This framing portrays biosecurity as a 'game' between the biosecurity authority (the principal) and vessel operators (agents). The role of the biosecurity authority is to configure the variable under its control (*control variables* including the vessel testing interventions and the severity of financial payoffs to vessel operators) such that the decisions made by autonomous vessel



Payoff matrix	VDE	VEP 4	VEP 5	VEP 6	VEP 7	VEP 8
Risk rating		High	High	High	Low	Low
Biofouling effort	$0	-$2,000	-$2,000	-$2,000	-$10,000	-$10,000
Premium/levy	$0	-$4,113	-$4,113	-$4,113	-$1770	-$1770
Inspection cost	-$20,000	-$20,000	$0	-$20,000	-$20,000	$0
Delay cost	-$100,000	-$100,000	$0	-$100,000	-$100,000	$0
Fine	-$20,000	$0	$0	-$20,000	$0	$0
Total	-$140,000	-$124,113	-$4,113	-$144,113	-$121770	-$1,770

Figure 3.Example payoff matrix for low-effort vessels (VDE: vessel denied entry; VEP: vessel entry pathway)

operators implement the stated (legislated) biosecurity objective. Where this outcome is achieved, the biosecurity system is referred to as *incentive-compatible*. Importantly, incentive compatibility cannot be achieved unless vessel operators *truthfully reveal information* needed to determine the risk rating of their vessels. Truthful revelation of information is a precondition

[6] VDE in Figure 3 refers to vessel denied entry.

for economic efficiency and efficacy in all markets. Markets that display this property are referred to as *information efficient*.

This economic framing of biosecurity enables the biosecurity authority to determine the optimal inspection regime where optimal is defined as the level and type of vessel testing needed so that 'the *dominant strategy*' of vessel operators is to truthfully reveal vessel information. Research reported in Appendix D reveals several findings from this approach to biosecurity.

1. Using example data, it was not possible to align self-interested vessel operators with biosecurity objectives by increasing the probability of inspection alone. A fine on vessel operators who falsely signal vessel information will be needed to achieve incentive compatibility.
2. The optimal probability of inspection can be determined by firstly setting the monetary value of the fine at the marginal cost of false signalling (i.e., the expected cost on other vessel operators of higher rates of inspection). Once this is established, it possible to identify the probability of inspection needed so that the dominant strategy of vessel operators is to truthfully reveal information needed to determine each vessel's risk rating.
3. This methodology could be used to determine the optimal inspection/fine settings needed to implement the current biosecurity objective or an alternative objective referred to as an efficient level of protection (ELOP).
4. Based on synthetic (but realistic) data assumptions, there appears to be scope to reduce the overall cost of biosecurity (including for vessel operators) if an ELOP objective were adopted through a biosecurity risk insurance mechanism. For vessels that invest low-effort in biofouling mitigation, analysis suggests potential efficiency gains of 57% in inspection and compliance costs, with these gains proving robust to premium variations (see Appendices D and G) .
5. A range of refinements could be considered to further improve the economic efficiency properties of a biosecurity system implemented through a biosecurity risk actuarial levy mechanism. These include: incentives linked to vessel reputation, expansion of the types of vessels with respect to the level of biosecurity effort, more complex vessel audit/inspection regimes; and the implications of systematic (un-priced) risk.
6. A more complex economic framing of the decision and control space will need to be developed to analyse these refinements. Computer-based hosting of the decision and control space and a program of laboratory-based experimental markets will be needed to refine the fine-scale rules of the insurance mechanism.

5. Conclusion and Recommendations

5.1 Key findings

1. Designing the biosecurity system to be incentive-compatible and information efficient can be expected to improve economic efficiency (e.g., lower costs) and efficacy.

Incentives matter! Incentives inherent in interventions should be checked and refined during the intervention-design stage, to avoid costly errors to the Australian economy, environment and community from rules that cause the 'wrong' stakeholder behaviour. CEBRA Project 21C has developed the only known tool that could assist biosecurity decision-makers in this task. The proof-of-concept *Incentive Diagnostic Tool* provides a methodology for designing interventions that align stakeholder incentives with desired behaviour, while minimising implementation costs.

2. Applying the tool will require a multidisciplinary team, each of whom plays a part in the design of the incentive-compatible policy.

Applying the tool in its entirety typically involves an interdisciplinary team — pathway experts, operations and regulatory staff, industry stakeholders, market design economists, and potentially actuaries. While pathway experts should be able to source the information required *diagnose* whether incentive problems exist, a market design economist will likely be required for the *design* of the incentive-compatible policy itself. Systematically capturing the tool's use cases will reduce the time taken in the design phase.

There is scope to focus solely on the diagnostic phase of the tool (a light-touch approach), in which staff could check incentives, modify policies as required, check incentives again, repeating this process until they can be sure the desired human behaviour will result. The policy outcome, however, is unlikely to be the least-cost way of achieving the desired behaviour — determining the most efficient policy will require application of market design economics.

3. The application of actuarial science in the biofouling domain could fundamentally change biosecurity risk management

The emerging capability to price biosecurity risk through the application of actuarial science has been demonstrated in the biofouling domain. This capability could fundamentally change the way that biosecurity could be managed in the economy. Actuarial pricing can be implemented as a market for biosecurity risk insurance contracts or as an actuarial levy on the creators of biosecurity risk.

Actuarial pricing of biosecurity risk has four key advantages:

1. Economic efficiency – actuarial pricing creates an incentive for risk-creators to change behaviour in ways that reduce their biofouling risk. This can reduce Australia's exposure to biosecurity threats. Optimal pricing will encourage risk-creators to adopt cost-effective risk-mitigation strategies.
2. Financial sustainability – actuarially based biosecurity levies establish a pool of funds that is sufficient to cover expected losses arising from biosecurity incursions into the future.

3. Timely response to incursions – the pool of funds created from a biosecurity risk insurance mechanism/actuarial levy would be available to immediately respond to exotic pest and disease incursions.
4. Equity – actuarial pricing ensures that risk-creators fund biosecurity activities in proportion to their risk status.

5.2 Recommendations

To take advantage of the outputs and outcomes of CEBRA Project 21C we recommend that:

1. Further testing and refining of the Incentive Diagnostic Tool take place, and results from its application to pathways be systematically captured.

To progress the proof-of-concept tool there is a need to further test it with a range of different 'types' of pathways. While use of the tool to solve the biofouling-type of incentive problems could occur relatively quickly, there is a need to test the tool on a range of other pathway problems. While investment in the skills of market design economists would be ideal in this process, this might not always be possible.

The options for using the tool are as follows:

- **i.** Full application of the tool – select the set of different types of pathway problems and apply all stages of the tool to each problem type, using specialist market design economists and DAFF experts. Systematically capture the solutions to save time when similar incentive problems appear on pathways. Efficient policies will be generated.
- **ii.** A light-touch approach – staff focus solely on the diagnostic aspect of the tool, repeatedly checking the incentives in the tool following policy tweaks until they can be satisfied that the desired human behaviour will occur. The least-cost way of achieving the desired behaviour is not likely under this approach.

2. The Incentive Diagnostic Tool be embedded within the department's policy design process.

Although there is little empirical evidence of the extent of incentive problems in biosecurity, most biosecurity problems (non-compliant behaviour) appear to arise from decisions made by stakeholders — people who are usually working for organisations with a financial interest in importing and exporting goods. This suggests that the diagnostic tool and subsequent involvement by incentive/market design experts should be systematically applied across all import pathways in Australia.

When ready for publishing, the tool should be made available on the department's intranet as a resource to guide policy officers in developing future regulatory policies. The Office of the Chief Regulatory Officer (OCRO) should consider how the tool can be promulgated through relevant officers, based on its ease of use. OCRO should consider opportunities to share the tool, findings of this report and other benefits of the project through regulator forums and communities of practice. Some consideration will need to be given to whether some internal staff should be trained to take people through the tool's process in initial stages and identify approaches for procuring specialised skills as required.

3. That investment be made into applying actuarial approaches to biosecurity risk management more broadly.

Actuarial pricing could be introduced to biosecurity risk management as either a formal market for biosecurity risk insurance or as an actuarial levy on risk-creators (higher risk = higher levy/premium), leading to significant efficiency gains. Further investment will be needed to apply actuarial methods to all classes of biosecurity risk faced by Australia including from imported goods, plants and animals, and inbound passengers.

Actuaries could also be engaged to assist the department develop risk management and mitigation strategies more generally. Actuarial models of biosecurity risk could be applied to identify the most cost-effective interventions in infrastructure development, investment in monitoring and surveillance etc., including the spatial distribution of this type of analysis.

Actuarial pricing could also provide a mechanism for policy makers to demonstrate the ‘true cost’ of the biosecurity system. This true cost encompasses both direct costs — inspections, surveillance, incursion response — and indirect costs borne by industry, such as environmental damage and lost market access. It is important to note that only a subset of these costs is insurable; specifically, only those losses that are measurable and clearly attributable to an incursion can be priced into the biosecurity insurance premium. Residual costs, such as public-good environmental impacts or systemic trade losses, would still require public funding. An insurance premium pool would therefore reduce, but not eliminate, the call on general revenue.

Actuarial pricing could therefore provide powerful policy analysis for demonstrating to decision makers rigorous assessment of the cost of the biosecurity system, potentially demonstrating the efficacy of existing or emerging regulatory interventions or justifying the holistic cost of the biosecurity regulatory system. This would improve advice to government and industry about the necessity of biosecurity and inform conversations about risk appetite.

4. Designed mechanisms that are developed using the Incentive Diagnostic Tool should be tested in an economics laboratory.

Laboratory testing of policies should be supported. Testing these mechanisms in the safe confines of an economics laboratory will produce estimates of the economic efficiency and efficacy advantages suggested by economic theory, and increase familiarity with the mechanism.

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Appendix A: The Incentive Diagnostic Tool

Incentive Diagnostic Tool

A self-diagnostic tool for biosecurity problems caused by human behaviour

MANUAL

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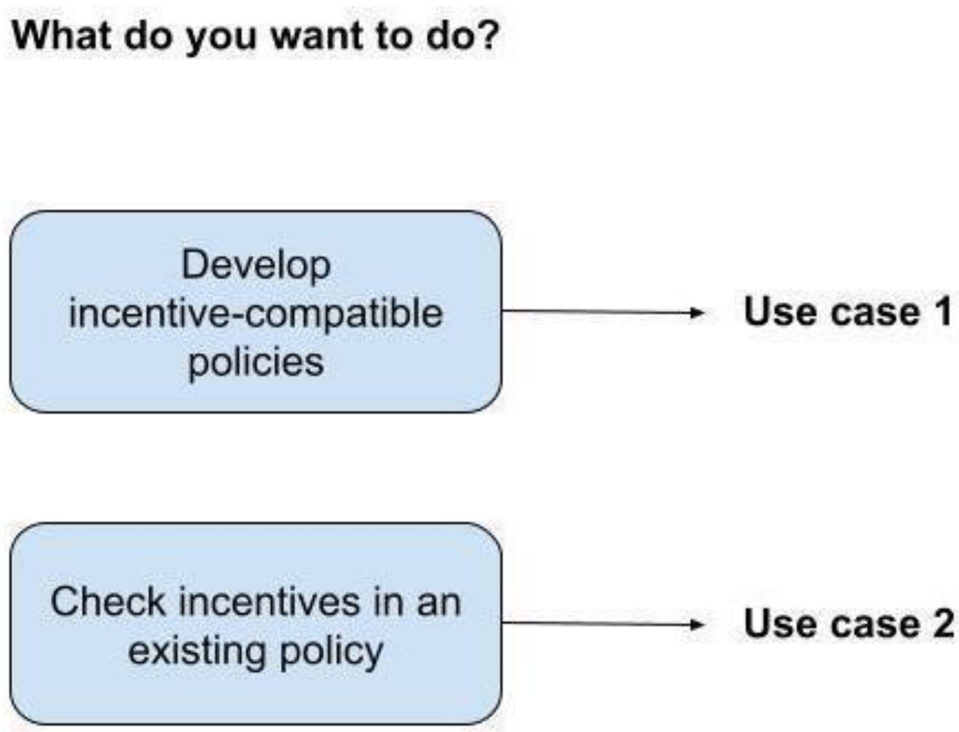
Centre of Excellence for Biosecurity Risk Analysis

Guide to the Manual and Tool



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1 Introduction and background

1.1 Purpose and scope of manual

This manual describes the *Incentive-diagnostic tool*. The tool is for checking the incentive properties of biosecurity interventions and for refining or developing interventions as necessary. Biosecurity interventions are broadly defined as the policies, rules, regulations, inspection regimes etc. which are developed and implemented with the aim of reducing biosecurity risks. Since every intervention carries with it incentives for humans to behave a particular way, it is important to carefully consider the design of interventions, to make sure their inherent incentives will actually lead to the desired behaviours.

There are typically a wide range of possible interventions that could be applied to change human behaviour for a given importing context. This manual explains a process to identify which interventions are “best” for a given pathway — the intervention which achieves the desired reduction in biosecurity risk at the lowest cost.

A rigorous process should always be used to design the biosecurity interventions needed to change human behaviour, to avoid unintended negative consequences related to non-compliance. The process described in this manual is based on a well-established set of ideas from the economics discipline.

1.2 Biosecurity risks and human behaviour

Australia faces many biosecurity threats from international trade pathways. The Australian Government Department of Agriculture, Fisheries and forestry (DAFF) acts to prevent animal and plant threats from entering the country by undertaking a range of interventions on import pathways. Although developing these interventions relies on deep technical knowledge of the relevant threat, the risk of exposure to many biosecurity pests and diseases is in part determined by the actions of individuals and organisations involved in import supply chains. These participants include overseas producers, importers, vessel owners, and third-party certifiers, all of whom make choices that affect biosecurity risks facing Australia — they may impose financial or environmental costs on the Australian economy, community and environment if their actions lead to pest or disease incursions.

The interventions imposed by DAFF include regulations and inspection regimes imposed pre-border and at the border, delegation of biosecurity functions to third parties, and reputational capital etc. Each of these interventions establish rules, rights, obligations, and processes that are, essentially, creating incentives for particular behaviours to occur. Ideally, the incentives created by the rules should result in supply-chain participants making choices that are consistent with the national biosecurity objectives of Australia.

Focusing on the incentive properties of rules is an important, and often neglected, part of designing biosecurity interventions. When the incentive properties of interventions aren’t given proper attention, well-intentioned biosecurity interventions can cause counterproductive consequences for the environmental, economic, and societal assets they are aiming to protect; human behaviour may actually be the opposite of what was intended by imposing the intervention.

1.3 Who is this manual for?

This manual is primarily for biosecurity agency staff who are responsible for designing or refining biosecurity interventions aimed at changing stakeholder behaviour to reduce biosecurity risks.

Since incentive problems such as those experienced in biosecurity are observed in most domains of the economy, the methodology outlined in this manual could be applied more broadly, with some modification.

1.4 How to use the manual and tool

This manual presents the *Incentive Diagnostic Tool* (the tool), its application using an example, and additional technical information on incentives.

There are two uses the tool:

1. to create a new biosecurity intervention that is incentive-compatible; and
2. to check and refine the incentive properties of an existing intervention.

The tool includes:

- a step-by-step diagnostic and economic framing component – Section 2;
- refinement of an existing intervention component – Sections 3; and
- a design component – Section 4.

The **diagnostic and economic framing component** is essential for both uses of the tool, i.e., whether the user is checking an existing intervention or developing a new intervention. The step-by-step guide enables biosecurity agency staff to systematically understand the incentives faced by relevant decision-makers who are subject to a biosecurity intervention. It does this through a sequence of questions (Section 2), the answers to which can be synthesised to understand how individuals make decisions that influence biosecurity outcomes and then how existing intervention parameters may be adjusted to induce beneficial changes in behaviour (Section 3).

In some cases, a full application of the tool may not be required or possible. A 'light touch' use of the tool focuses on the design and economic framing component alone. Where incentive issues are identified, pathway managers would adjust the policy and work through the steps in Section 2 until incentive compatibility is reached.

Depending on the complexity of the incentive problem identified, the **design component** (Section 4) aims to either identify refinements to the existing interventions or identify the class of 'mechanism' and the specialised economic design skills needed to achieve the most efficient and effective biosecurity interventions.

Note. The tool described in this report applies economic concepts, typically used by economists with training in market/mechanism design. We have included relatively simple examples to assist non-economists use the tool. In some instances, the complex nature of behaviours on a pathway may require a combination of specialist pathway knowledge and market/mechanism design expertise to appropriately design an intervention with the desired incentive properties.

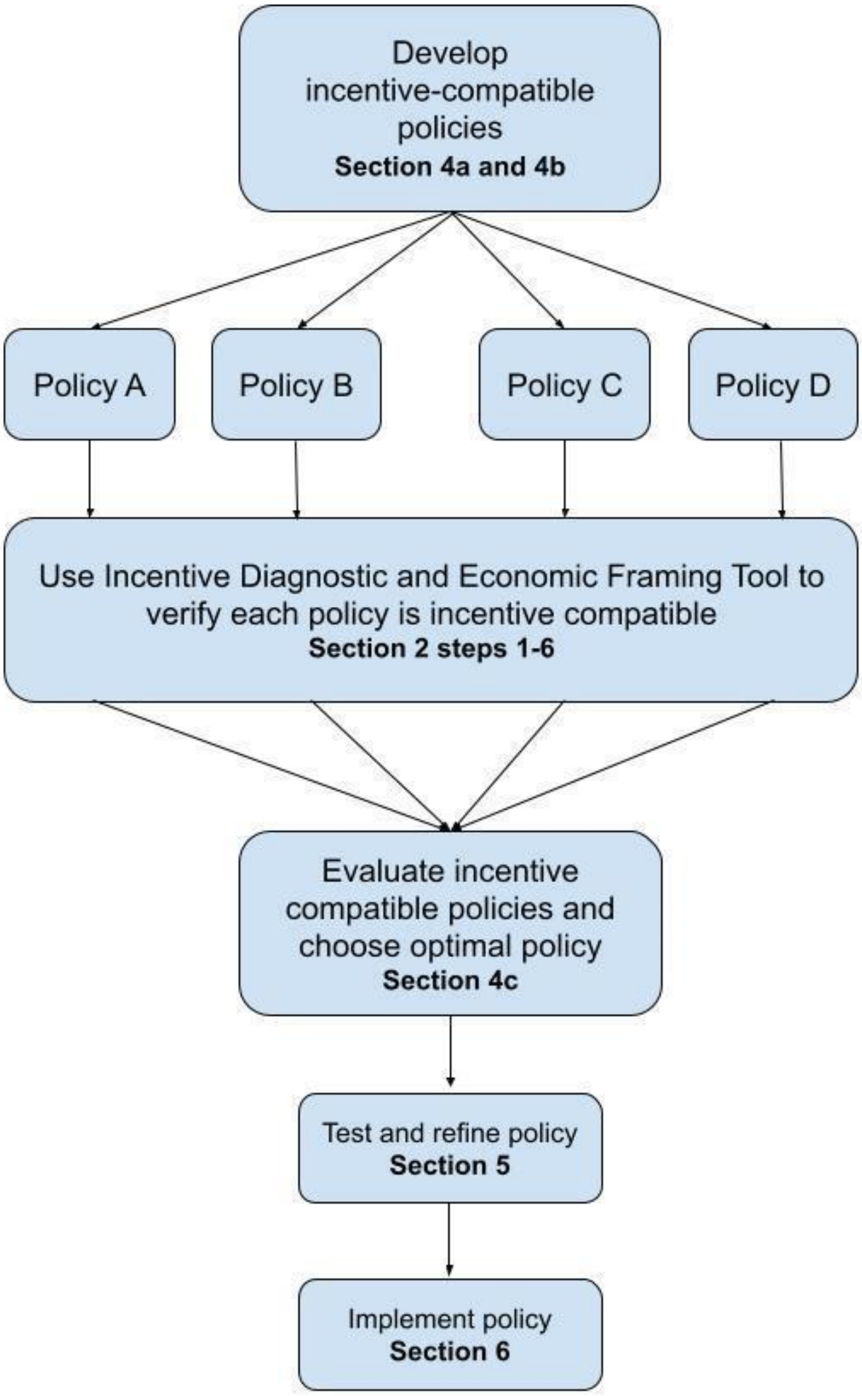

Figure A. 1. The process for creating the "best" interventions for a specific biosecurity pathway.

1.5 Use case 1 — Create incentive-compatible biosecurity interventions

The process for using the tool to design incentive-compatible interventions (policies), select and implement the best of these, is shown in Figure A.1. The 'best' intervention will be the set of rules, processes, technology and incentives that achieve the stated biosecurity objective at the lowest cost.

Detailed instructions are given in each section. In summary, when fully applying the tool, users should proceed as follows:

Step 1. develop one or more candidate interventions that are incentive-compatible using **Sections 4a and 4b**, which details the process of developing incentive-compatible policies from scratch;

Step 2. check interventions for incentive compatibility using the Diagnostic and Economic Framing steps contained in **Section 2**, working through questions in 2.1 to 2.6. and providing answers where information is available;

Step 3. where incentive issues are found at 2.6, a decision can be made to either:

i) Adjust interventions via **Section 3** and then proceed to **Step 4**);

ii) Proceed with the intervention/s for which no incentive issues are found;

Step 4. evaluate the set of incentive-compatible interventions and choose the most efficient intervention using **Section 4c;**

Step 5. test the robustness of the proposed intervention and refine as necessary via **Section 5; and**

Step 6. Implement the intervention i) into practice or ii) via a field trial, and evaluate the impact of the intervention on behaviour and quantify its benefit, see **Section 6.**

For the light-touch approach to achieving incentive-compatibility, users should proceed as follows:

Step 1. develop one or more candidate interventions;

Step 2. check interventions for incentive compatibility using the Diagnostic and Economic Framing steps contained in **Section 2**, working through questions in 2.1 to 2.6. and providing answers where information is available;

Step 3. adjust the intervention option and repeat Step 1 until incentive compatibility is achieved; and

Step 4. move to practical implementation and monitor outcomes to ensure the expected behavioural responses occur.

1.6 Use case 2 — checking and refining the incentive properties of an existing intervention.

When behaviour on a pathway does not appear to be aligned with the purposes of the intervention, one may undertake a check of the incentive properties of the existing intervention and, in the event there is an incentive issue, refine the intervention to improve behaviour. Refining an intervention may be a preferred alternative to completely redesigning it, because fewer departmental resources may be required to attain a satisfactory outcome. This may be achieved through adjusting how some elements of the intervention are implemented, for example: the frequency of inspections; the types of intervention responses to identifying potential non-compliance; and/or the use of information in the intervention.

The process for using the tool to check and refine the incentives of an existing intervention is shown in Figure A.2. Detailed instructions are given in relevant sections. In summary, to find the most efficient incentive-compatible intervention (full tool application), users should proceed as follows:

Step 1. use the Diagnostic and Economic Framing steps in **Section 2** to identify source/s of the incentive problem, if not known already;

Step 2. determine the intervention parameters that can be adjusted to make the intervention incentive- compatible, using **Section 3**;

Step 3 create new incentive-compatible intervention options;

Step 4 calculate the total costs from introducing incentive-compatibility to each intervention , using **Section 3**;

Step 5 choose the least-cost option;

Step 6. **(Optional)** test the robustness of the proposed intervention and refine as necessary via **Section 5**;

Step 7 implement the intervention i) via a field trial; or directly into practice or ii), and

Step 8 evaluate the impact of the intervention on behaviour and quantify its benefit, see **Section 6.**

For the light-touch approach to achieving incentive-compatibility, users should proceed as follows:

Step 1. use the Diagnostic and Economic Framing steps in **Section 2** to identify source/s of the incentive problem, if not known already;

Step 2. adjust the policy option and repeat Step 1 until incentive compatibility is achieved; and

Step 3. move to practical implementation and monitor outcomes to ensure the expected behavioural responses occur.

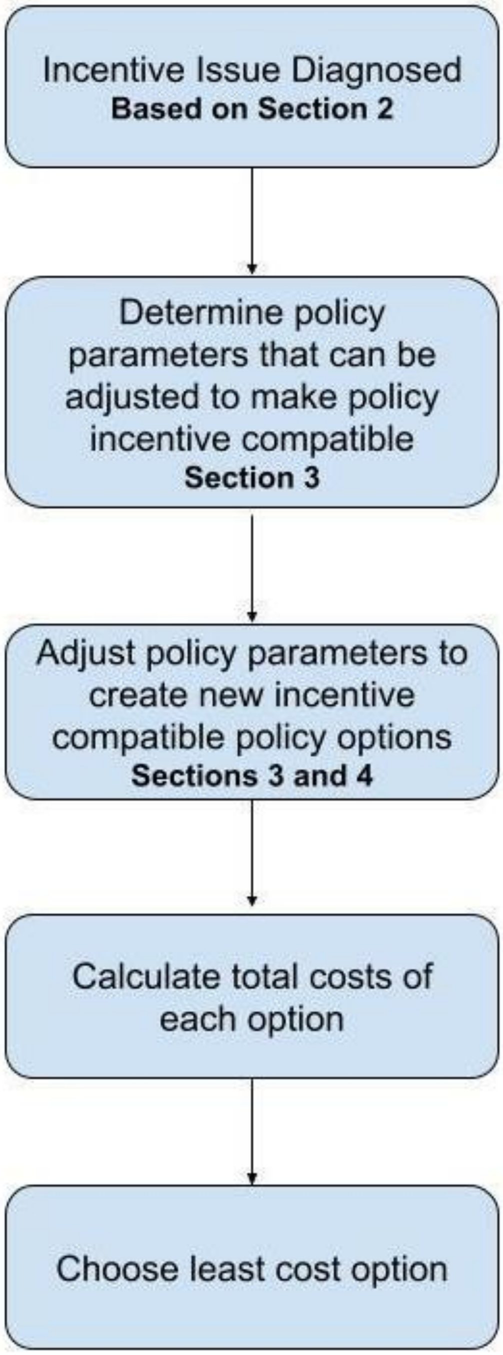

Figure A. 2. The process for refining interventions for a specific biosecurity pathway, and the sections of the report in which each is discussed.

2 Diagnostic and Economic Framing

The six steps outlined in this section form a method for either diagnosing a potential incentive problem on a pathway, or as an economic framing method for understanding the incentive properties of an existing or proposed intervention. Each step is explained using the hypothetical hypoanimals pathway described in Box 1.

Staff should work through each of six steps in this section as best they can, and make a conclusion about the incentive-compatibility of an intervention at Step 6. Where it is difficult to answer questions, a response of ‘unclear’ or ‘not known’ should be given.

Box 1. Imports of hypoanimals into Australia (a hypothetical case study)

Conditions around the importation of hypoanimals into Australia are primarily focused on sickens virus (SICK) risk mitigation. SICK is a zoonotic, viral disease present in more than 20 countries across the globe and is responsible for an estimated 1,000 human deaths each year globally.

Hypoanimals being brought to Australia from other countries must be covered by an import permit. DAFF has also imposed pre-export and post-arrival biosecurity measures, including off-shore veterinary health certification attesting to preparations performed to manage the biosecurity risk from SICK.

Since 2020, there have been significant changes on the hypoanimals pathway, including:

- increasing demand for hypoanimals which has led to an increase in their value;
- a change in the profile of exporting countries to those where SICK virus is known to occur;
- increasing commercialisation of trade and
- increases in suspected intentional non-compliances including fraud.

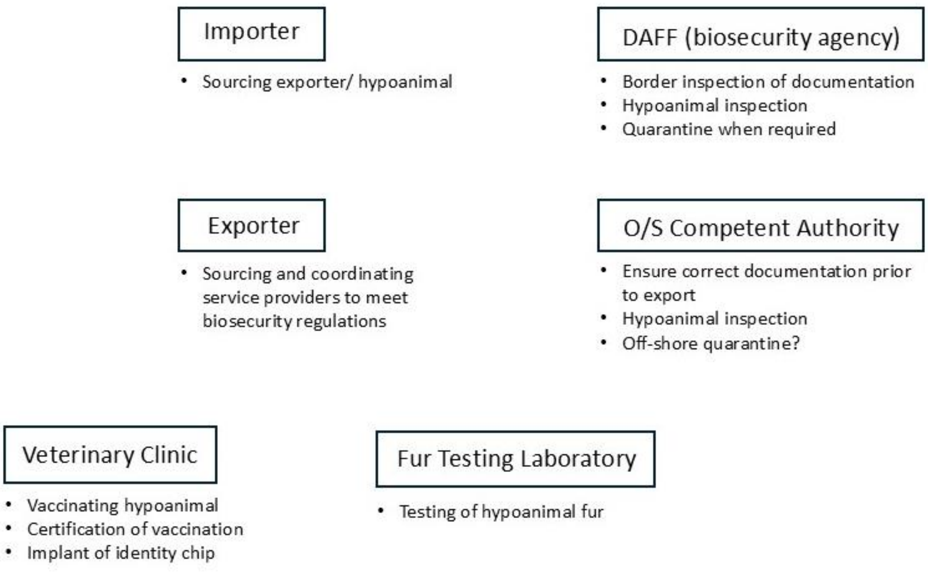

Figure A. 3. Participants in the hypoanimals pathway and the activities undertaken to manage the risk of SICK, drawn from the information provided in Table A.1 and arranged for ease of exposition with diagrams that follow.

2.1 Step 1: Participants and compliance

The goal of this initial step is to identify the relevant decision-makers and how they contribute to managing biosecurity risk along the pathway. This information will assist in building up a conceptual representation of the pathway. A representation of the relevant decision-makers on the hypoanimals pathway and the activities they carry out to mitigate the risk of sickens virus (SICK) — drawn from Table A.1 — is shown in Figure A.3.

Table A.1. Questions regarding key pathway participants and their activities; example answers given for the hypoanimals pathway

No.	Question	Example answers: hypoanimals
1	Who are the participants on the pathway (e.g businesses, end-consumers, regulators, etc.)?	● DAFF (biosecurity regulator) ● Domestic consumers/brokers ● Importers ● Exporters ● Off-shore (O/S) Competent Authorities (CA) ● O/S veterinary clinics ● O/S fur testing laboratory
2	What are the actions that each participant in (1) undertakes to manage the biosecurity risks?	**DAFF** ● Checks documentation at border inspections ● Inspects hypoanimals ● Quarantines hypoanimals if required **Importer** ● Sources exporter/hypoanimals **Exporters** ● Sourcing and coordinating service providers to meet biosecurity regulations **O/S CAs** ● Ensure correct documentation prior to export ● Hypoanimal inspection ● Off-shore quarantine **Offshore veterinary clinics** ● Certifies hypoanimal's health **Offshore fur-testing laboratory** ● Testing of hypoanimal fur
3	Does each participant understand (are aware of) their responsibilities under the intervention?	Yes: DAFF has audited CAs who in turn licence veterinary clinics and laboratories according to Australian biosecurity requirements. The auditing only occurs once — prior to trade commencing.
Notes		

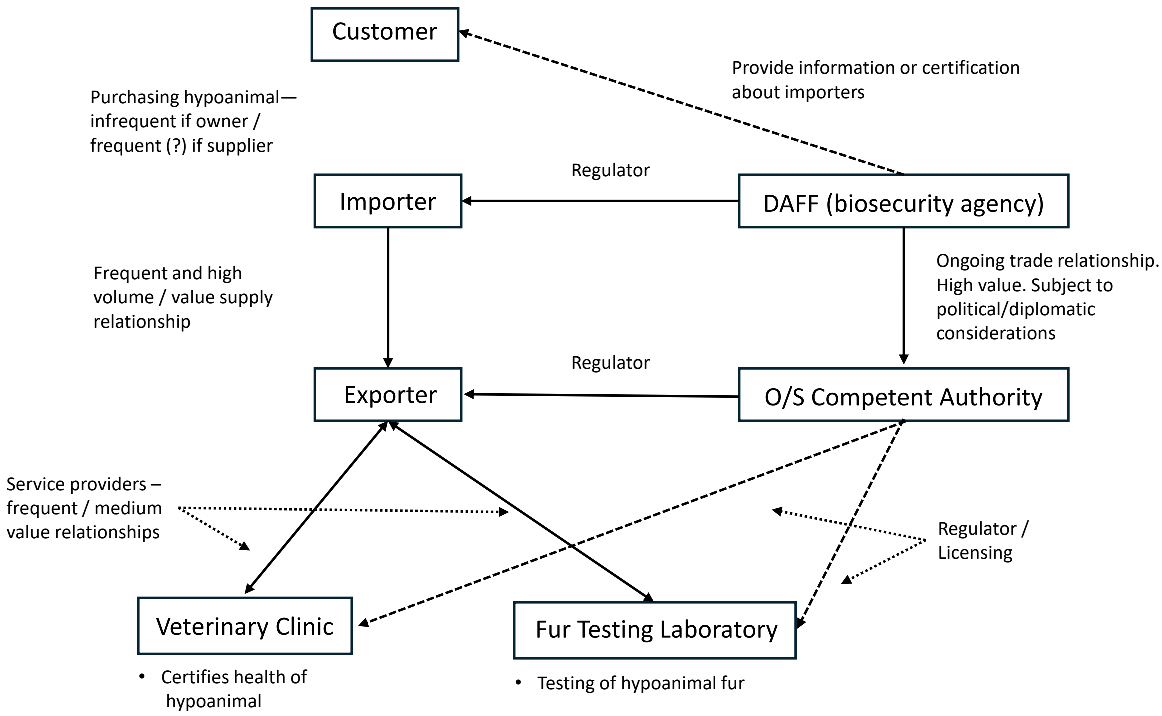

Figure A. 4. Current regulatory functions and responsibilities within Australia's biosecurity system for the hypoanimals pathway, information drawn from Table 2 and Figure A1. Dashed lines indicate potential relationships.

2.2 Step 2: Relationships

The next step is to understand the relationships between each of the decision-making entities identified in the first step. These relationships may take a number of forms depending on the entities involved, the requirements of the policy and the nature of the product supply chain itself. The relationships between decision-makers are identified via questions listed in Table A.2. A representation of these relationships is given in Figure A.4.

Table A.2. Questions about relationships between each of the decision-making entities identified in Step 1; example answers given for the hypoanimals pathway

No.	Question	Example answers: hypoanimals
1	What are the economic/regulatory relationships between the entities detailed in step 1?	**DAFF to customer:** DAFF provides information about certification of importers **DAFF to importer**: DAFF regulates, inspects documents and hypoanimals **DAFF and CA**: DAFF authorises CA to certify health status of hypoanimals **CA to Exporter**: CA regulates exporter **CA to Vet Clinic/Fur testing lab:** CA regulates and licenses both **Exporter and Vet Clinic/Fur testing lab:** Vet clinic and labs supply fur-testing services to exporter
2	Are the relationships repeated (ongoing)?	Repeated/ongoing relationships: ● DAFF and Importer ● DAFF and CA ● Importer and Exporter ● Exporter and Vet-Clinic/Labs
3	Are there financial transactions between the entities?	Yes, financial transactions occur between the following: ● Importer and Exporter ● Exporter and Vet-Clinic/Labs
4	If a product or service is being supplied/purchased, is the quality relevant/observable to both parties?	Whether a hypoanimal meets Australian biosecurity regulations is not readily observable directly. It relies on certification by overseas vet-clinics, fur-testing labs and CAs
Comments/Notes		

2.3 Step 3: The nature of (potential) non-compliance

This step describes the types of non-compliance that occur or could occur on a pathway. In the diagnostic usage of the tool, the type of non-compliance may be readily identified. In an economic framing, the policy maker may need to consider different modes of potential non-compliance that may involve some coordination amongst pathway entities. For instance, falsification of certification may require coordination between importer/exporters and certifying entities. A representation of beneficial relationships between parties is given in Figure A.5, based on information in Table A.3.

Table A.3. Questions that seek to uncover non-compliant behaviour and its cause/s; example answers given for the hypoanimals pathway

No.	Question	Example answers: Hypoanimals
1	What are the non-compliant behaviour(s) and which entities are responsible for these?	Falsification and manipulation of fur testing: Fur testing lab; Vet clinic False certification of health status: Vet clinic
1a	• Are these non-compliant behaviours concentrated amongst a subset of entities?	Yes
1b	• Is coordination across multiple decision-makers required to successfully (derive benefits from) avoid the intent of the policy?	Yes
2	Are there benefits from the non-compliance and who do these directly accrue to?	Anecdotal evidence suggests that customers are willing to pay significant premiums to bypass biosecurity requirements. The benefits for bypassing these can be large and we assume a $5,000 benefit per hypoanimal (Fig A.5). From this, the importer pays upstream participants compensation for risks of detection/consequences — $A, $B and $C.
2a	• Are the benefits from avoided costs of meeting the policy/regulatory requirements?	The fixed costs of fur testing are small relative to the benefits that exist for reducing the time animals spend meeting offshore biosecurity requirements.
2b	• Are the benefits derived from higher prices?	Yes
3	Are the benefits readily transferable between different entities?	Yes
3a	• Can the benefits or cost savings be dispersed from the entities that directly receive them to the entities that are responsible for non-compliant behaviour?	Yes — ongoing financial relationships allow payments to readily transferred/dispersed
3b	• If so, what is the nature of the transfer?	Financial payments
Notes		

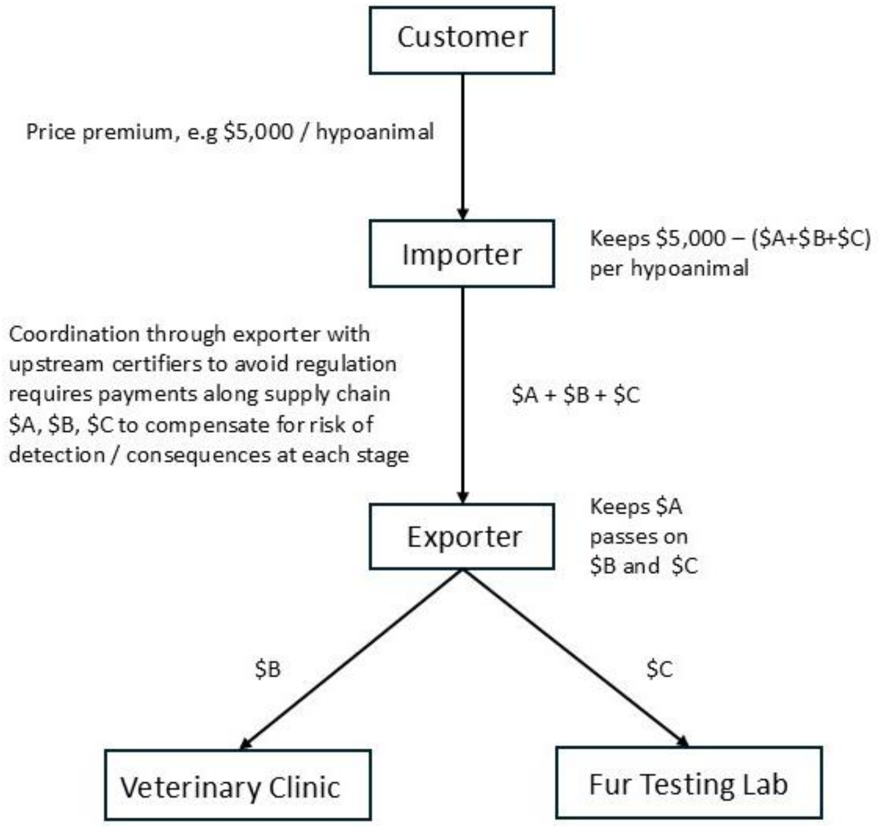

Figure A. 5. A depiction of the benefits to each party from the transactions between them, drawn from Table A.3. Note the amount of benefits is for illustrative purposes.

2.4 Step 4: Measurement

The aim of this step is to understand the approximate probability of a non-compliant behaviour being measured and triggering a response by the policy.

Table A.4. Questions that seek to understand measurement of non-compliant behaviour; example answers given for the hypoanimals pathway

No.	Question	Example answers: Hypoanimals
1	What is measured by Australia biosecurity about compliant/non-compliant behaviour and how frequent and precise are these measurements?	Inspection of documents: ● Non-compliance – evidence of not obtaining certification or meeting testing requirements for biosecurity ● Compliance – unable to detect deliberate avoidance by exporter Inspection of animal for evidence of SICK: ● Evidence of disease → likely non-compliance ● Lack of evidence →not very informative because underlying probability of SICK is low Quarantine/observation: ● Evidence of disease → likely non-compliance ● Lack of evidence → not very informative because underlying probability of SICK is low Potential testing for markers of treatment for SICK: ● At the Australian border, individual tests are a weak indicator of whether treatment/biosecurity requirements have been met because of the time between treatment and arrival. ● Across multiple hypoanimals it may detect systematic avoidance. ● Expensive and infrequently applied.
2	What is measured by the O/S Competent Authority (or other relevant parties) about compliant/non-compliant behaviour and how frequent and precise are these measurements?	Inspection of documents ● Unable/unlikely to detect deliberate avoidance by exporter Inspection of hypoanimal ● Likely non-compliance if evidence of disease, however, no evidence of disease is not very informative of compliance/non-compliance. Oversight of Veterinary Clinics and Fur Labs ● Unclear how much/if any oversight of the behaviour of fur labs/veterinary clinics
3	Do the relevant entities anticipate that these measurements are being made/observed?	Yes

3a	• Do they approximately understand the frequency/precision of the measurement?	Yes
Notes		

2.5 Step 5: Consequences

The aim of this step is to describe what happens to import supply chain participants if non-compliance is detected. They could face direct costs (e.g., paying for extra biosecurity measures or being fined) or indirect economic costs (e.g., delays clearing the border or being treated more strictly under future policies).

Table A.5. Questions around consequences of non-compliant behaviour; example answers given for the hypoanimals pathway

No.	Question	Example answers: Hypoanimals
1	What are the potential consequences from measurements consistent with non-compliance for the source(s) in Step 4 and to whom can these be applied? • When are these penalties applied in practice or what is the trigger for these to be implemented?	DAFF • If the hypoanimal is identified as posing a risk then it may be euthanised. • Limited scope for consequences otherwise. In part, this is because the identity of the importing entity is not readily identified by the regulatory authorities. O/S Competent Authority • None/limited
2	Are these credible/understood by the relevant entities?	There are limited consequences, and this is likely understood by the relevant entities.
Notes		

2.6 Step 6: Construct decision-maker's trade-off(s)

Step 6 involves using the information derived in steps 1-5 to understand whether the decision-maker will comply with the proposed or existing intervention, or not.

A stylised depiction of a decision maker choosing whether to engage in a strategy to avoid (Avoidance) or comply with the rules and processes created by the biosecurity authority (No-Avoidance) is shown in Figure A.6. Information from the hypothetical but plausible hypoanimals example is given in the blue band, with additional information in 2.6.1.

In a nutshell, the decision-maker will compare the costs and benefits of compliance with those for non-compliance. This is the decision-maker's 'trade-off'. This trade-off needs to be evaluated to determine whether the intervention contains the *right* incentives i.e., that the No Avoidance strategy will be the preferred one.

Where there are multiple agents involved in the supply chain, avoidance requires coordination along the supply chain i.e., it will be unsuccessful if any of the decision-makers do not engage in avoidance behaviour. The distribution of the benefits from avoidance across the supply chain may be adjusted/determined in order to achieve avoidance. The relevant comparison in this case is whether the total benefits are sufficient to induce avoidance behaviour by all the relevant entities.

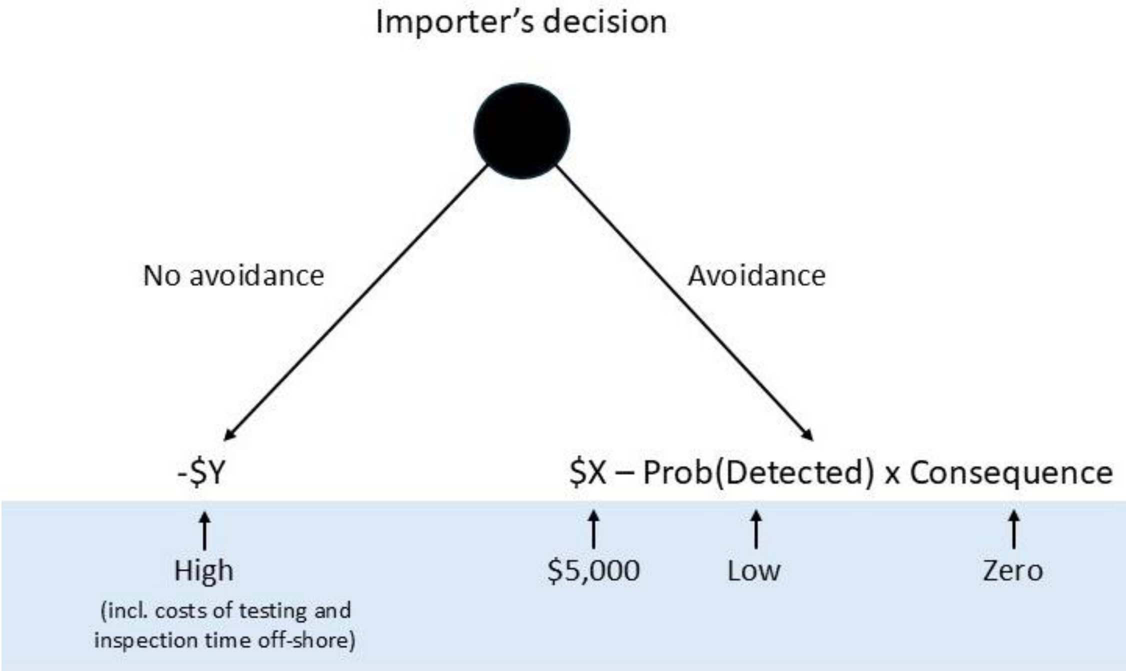

Figure A. 6. Example of decision-maker's trade-off. Information from Steps 3-5 is used to illustrate the trade-off for importers of hypoanimals is shown in the blue band.

To construct the decision-maker's trade-off, proceed as follows:

Step 1. Determine the following values:

- ***Y:*** the cost ($) of compliance with the biosecurity intervention (i.e., the cost of undertaking a particular treatment in order to be compliant);
- ***X***: the amount gained ($) from avoidance (e.g., by skipping a costly compliance action, products may arrive faster or in better condition and thereby sell at a premium);
- ***Detect*****:** the probability that non-compliance will be detected, (e.g., inspection should identify non-compliance with a probability of *Detect*); and
- ***Penalty***: the penalty/consequence ($ or $-equivalent) that is incurred as a result of detecting non-compliance (e.g., the import may be destroyed and/or

the importer may pay a fine, or the shipment may be delayed and goods deteriorate in quality).

Step 2. Determine:

- the net benefit from Avoidance: *X – Detect × Penalty*[1] ; and
- the cost from No Avoidance: *– Y*

Step 3. Check whether importers have an incentive to choose No avoidance/compliance (no incentive issues are present) or Avoidance behaviours/non-compliance (incentive issues are present). For importers to comply with biosecurity regulations, the benefit from compliance must outweigh the expected benefits of non-compliance; i.e., **check**:

Detect × *Penalty* > *X* - *Y*

Step 4. Form a conclusion about the existence of incentive issues on the pathway:

- no issues: exit tool (for an existing policy) or **Section 5** or **Section 6** (for a new policy);
- incentive issues, Use Case 1: go to **Section 4**; or
- incentive issues, Use Case 2: go to **Section 3**;

2.6.1 Hypothetical example — Hypoanimals

In the hypothetical example, compliant importers of hypoanimals into Australia face significant costs in preparing hypoanimals for export (Figure A.6), sharing these expenses with the multiple agents involved in the supply chain. This can be compared with the profit gained from avoiding import rules, where the likelihood of detection is low, and no penalties can realistically be levied on the importer if they are detected being non-compliant (Figure A.6).

There is likely to be an incentive problem on the hypoanimals pathway if the total benefit from avoidance ($5,000 in our example) can be split up along the supply chain in such a way that each decision maker will engage in avoidance behaviour. That is $X > *Prob(Detected) x Penalty*. In this example, this is possible when:

$$\$5{,}000 > PC_{Importer} + PC_{Exporter} + PC_{Vet} + PC_{Lab}$$

where PC is *Prob(Detect) x Penalty* for each entity (Figure A.6). The lack/unavailability of precise information/measurement of avoidance behaviour, and also the inability to identify or credibly implement sufficient consequences on the various parties, suggest that there is a potential incentive issue across the hypoanimal supply chain.

Note also, that the scale of the problem may be even more severe when the number of hypoanimals increases, but the probability of detection and consequences do not increase in proportion.

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[1] Note that the *Frequency* that a good/shipment is inspected for compliance could also be included here, but is kept out for simplicity.

2.7 Additional Technical details

There are two important components of the stakeholder's trade-off (Figure A. 6):

i) some monetary $ amount is gained from avoidance (e.g., by skipping a costly compliance action); and

ii) there is a chance of incurring a given financial penalty (consequence) depending on the expected probability of detection.

Each agent would evaluate and compare the expected costs and benefits of both the 'No-avoidance' and 'Avoidance' options in determining their strategy. From this framing, it can be seen that the strength of financial gains from an Avoidance strategy, the target biosecurity outcome (e.g., zero risk of SICK entry), the probability of detection and the consequences of being caught must be considered in defining the 'best' inspection strategy. For example, a decision maker would choose Avoidance when:

$$\$(X+Y) > Detect \times Penalty$$

In some cases, avoidance may require multiple parties to coordinate their activities and divide the net benefits amongst themselves. When the benefits can be relatively easily transferred between these parties then one may aggregate the benefits and costs and compare it to the sum of each party's *Detect x Penalty*. This is illustrated for the hypothetical hypoanimal case below (3.1.1).

This simple framing of how decision-makers identify their strategic interaction with the biosecurity agency has a number of important implications with respect to the design of biosecurity systems. By designing the rules, processes and incentives, the biosecurity agency can influence the behaviour of agents. From Figure A. 6 it can be seen that the biosecurity agency can influence two settings. The first is by altering the probability that agents taking the 'Avoidance' strategy will be detected. For example, the biosecurity agency could invest in technology that improves the accuracy of testing procedures and or by increasing the sample fraction. Both of these are costly activities for the biosecurity agency. The second option could be to change the consequences of Avoidance (i.e., the severity of penalties). An optimal inspection strategy can be identified by considering the costs and benefits of such changes.

A range of other factors can also be included in the decision-maker's environment to improve the efficacy and cost-effectiveness of the biosecurity system. These include:

- *Repeated interactions* – Figure A. 6 depicts the decision a regulated entity makes to avoid or not avoid regulation in a single instance. In reality, for many activities, agents repeatedly interact with the biosecurity system such that their reputation can be used as an incentive. Reputation is used in many markets (e.g., Uber, eBay) to influence behaviour on both sides of the market. When reputation is added to the decision environment in Figure A. 6, it creates scope for the biosecurity agency to improve the efficiency and efficacy of the system but also creates information and incentive dimensions to the design problem.

- *Differences between agents* – Each agent that interacts with the biosecurity agency is likely to be different (different 'types'), displaying differences with respect to risk aversion (some have a higher appetite for risk-taking behaviour), cost structures, commercial incentives and other behavioural attributes. In this environment, each agent is likely to have different behavioural responses to a given set of rules, processes and incentives that define the biosecurity system such that one biosecurity setting (size) will not fit all agents. This diversity is important for the design of the rules, processes and incentives that define the biosecurity system.
- *Delegation of biosecurity functions* – Some biosecurity functions can be, and often are, delegated from the biosecurity agency to an agent (e.g., an importer, incoming vessel, testing authority) further complicating the environment in which decisions are made (see Campbell et al., 2021). In some instances, delegation is initiated so that risk assessments are made pre-border (lessening the biosecurity loss exposure) but these arrangements can also increase biosecurity loss exposure because the biosecurity agency no longer has direct line of sight to the problem. Whilst these arrangements create a more complex decision-making environment, and require specific types of interventions, they can also be framed as games of chance and reward as illustrated in Figure A. 6.
- *Information complexities* – Regulation of entities relies on receiving truthful information from them about their regulated activities — whether it's the goods, conveyance, or their practices. When developing incentive-compatible policies, it's important to account for hidden information or actions[2] that could affect how efficient or effective a policy is. Entities may make strategic choices if they believe doing so benefits them — for example, by withholding information or misreporting to avoid costs. As such, policies should be designed to encourage behaviours that minimise the likelihood of information or actions being hidden. We should also be mindful of unintentional non-compliance — such as false positive animal health tests — and ensure policies remain robust under these conditions.

Given the range of biosecurity pathways, differing objectives for pathways, technology and inspection options that exist in the real world, a one-size-fits-all regulatory approach will not apply to all situations. Systematic analysis of decision points, types of decision-makers, biosecurity objectives, information complexities, delegations, decision pathways, types of incentives etc. will be needed to determine the incentive structure needed to align the actions of self-interested agents with the objectives of the biosecurity objectives of each pathway.

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[2] *Hidden information* problems generally occur before the border and *hidden actions* occur after the border. The latter are relevant where biosecurity tasks are delegated from the biosecurity agency to a third party.

3 Optimising an existing policy/regulation

One use of the Incentive-diagnostic tool is to check whether an existing intervention is likely to suffer from an incentive issue. That is, some of the relevant parties subject to the regulation may not act in a way that is consistent with the intention of the intervention.

When an incentive issue has been diagnosed it may be possible to address the issue through adjusting how the measurement and consequence elements of an existing policy are implemented. There are costs associated with the measurement and consequence elements of a policy that influence whether to adjust the policy or to proceed to redesigning the policy. The policy maker may face a choice at this point about whether to undertake changes to the existing policy or to undertake a more comprehensive incentive-design exercise.

In principle, the policy maker must consider whether it is possible to make the existing policy incentive-compatible and, if so, whether doing so will introduce significantly higher pathway costs. We illustrate this decision process in Figure A. 7.

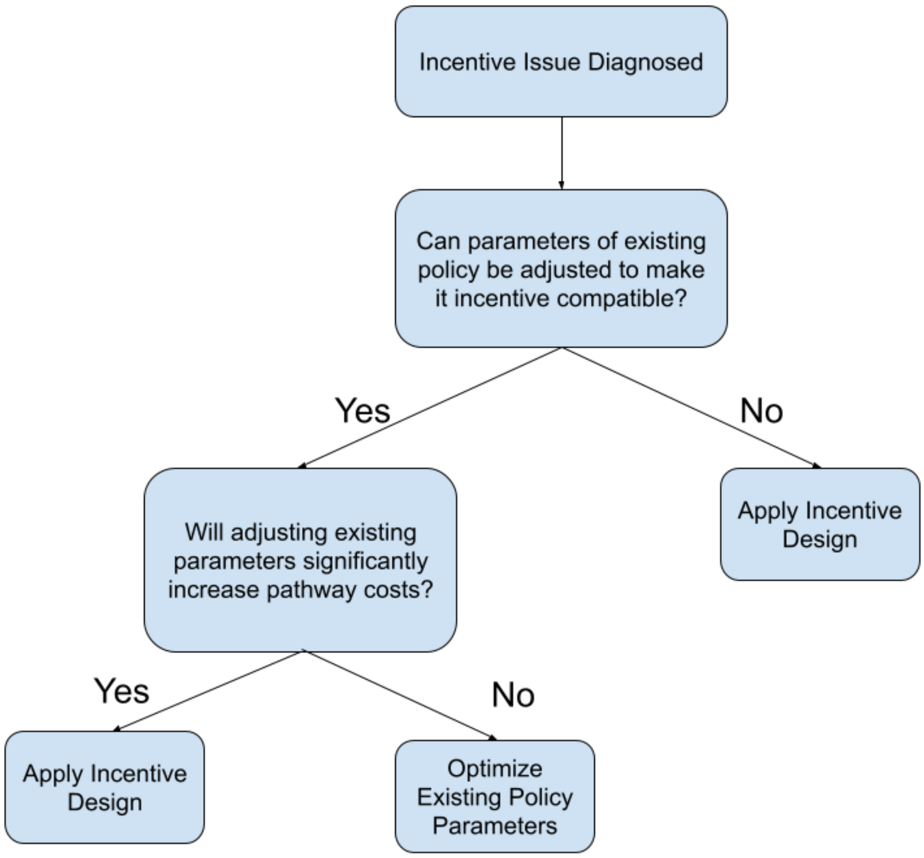

Figure A. 7. The process for deciding whether to adjust the policy or to proceed to redesigning the policy

There are two types of costs that are relevant:

- immediate costs of measuring behaviour through inspections/testing; and
- costs associated with created incentives due to imperfect measurement.

Costs arising from inspections/testing are straightforward to understand. Potentially the less obvious source of costs arises from imperfect measurement. In the following subsection we describe the costs associated with imperfect measurement and the connection to the measurement/monitoring technology.

Imperfect Measurement

An important concept is *imperfect measurement* — understanding how the measurement technology and consequence elements of a policy interact to create "incentive costs" on a pathway. Imperfect measurement occurs when behaviour on the pathway is consistent with the intention of the policy (i.e., regulated entities are choosing actions that the policy is intended to generate) but the measurement suggests it is inconsistent with the policy; and the policy specifies a consequence (as part of its incentive-compatible design).[3]

The concept of imperfect measurement is illustrated in Table A.6, where the percentages shown in the table correspond to the likelihood of each measurement (Pass – Fail) when behaviour is compliant or non-compliant. The measurement technology is informative about whether behaviour is likely to be compliant/non-compliant: a *Pass* when behaviour is compliant occurring with 80% probability, and a *Fail* occurring when behaviour is non-compliant with 90% probability. However, the measurement is imperfect because 20% of the time a measurement of *Fail* occurs when behaviour is compliant (false-negative) and 10% of the time a measurement of *Pass* occurs when behaviour is non-compliant (false-positive).

The consequence of imperfect measurement is that even when behaviour is consistent with the policy (compliant) the policy will impose some consequence in the event of a false-negative measurement. Absent additional sources of information to further detect the type of behaviour, this is an unavoidable cost of creating incentives on a pathway (incentive-cost).

Table A.6: Imperfect Measurement Example

	Compliant	**Non-compliant**
Pass	80%	10%
Fail	20%	90%

[3] This concept is known as a false-negative in statistics

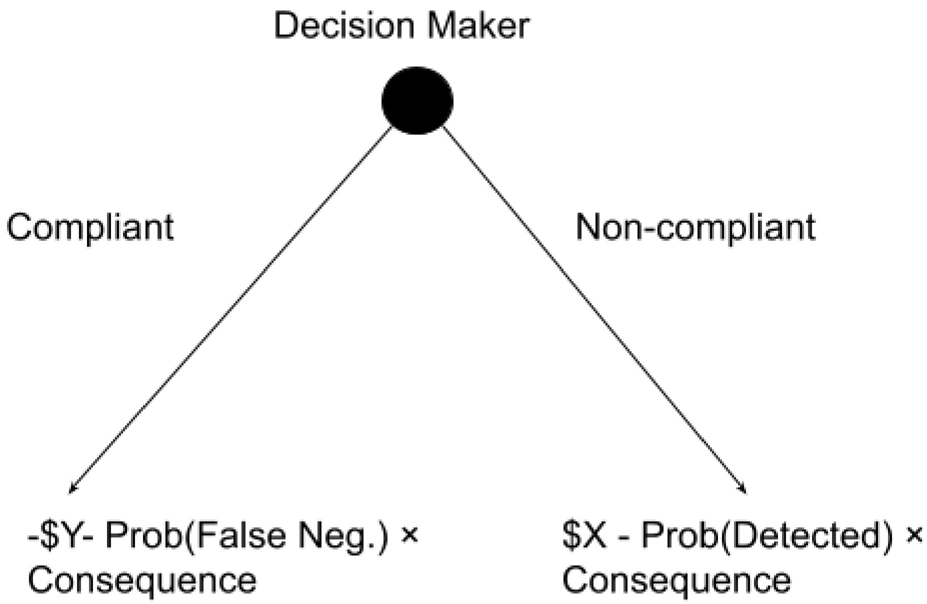

Figure A. 8. Imperfect Measurement Decision Example

In this example, the "incentive cost" is given by the expected amount that a compliant entity suffers a consequence $Pr[False\ Neg.] \times Consequence$ (Figure A. 8). This represents an additional cost to any entity from using a pathway, from the need to provide incentives under imperfect measurement. In particular, imprecise measurement technologies (high probabilities of generating false positives) and large policy consequences after a false positive increase the costs of using a pathway. To mitigate these costs, particularly where non-market impacts are significant (e.g., the euthanasia of hypoanimals), policy designs could incorporate a right of review for negative test results. This mechanism allows for re-testing, enhancing confidence in outcomes and reducing the severe consequences of potential false positives for compliant entities.

Incentive Compatibility under imperfect measurement

A simple decision node with imperfect measurement is shown in Figure A. 8 In the presence of imperfect measurement the compliant action is preferred to the non-compliant action (i.e., it is incentive-compatible) provided that:

$$-Y - Pr[False\ Neg] \times Consequence\ >\ X\ - Pr[Detected] \times Consequence$$

which occurs when:

$$(Pr[Detected] - Pr[False\ Neg]) \times Consequence\ >\ X\ + Y$$

Conversely, if a policy is not incentive-compatible then the reverse holds. A policy may be adjusted to achieve incentive compatibility by increasing (i) $Pr[Detected] - Pr[False\ Pos]$ or (ii) the *Consequence* amounts so that the relationship is satisfied.

Optimal Policy

An optimised policy ensures that the incentive-compatibility relationship is satisfied while minimising the combination of direct costs and the 'incentive costs' of the policy. Adjusting a policy that is not incentive-compatible requires increasing either or both of:

(i) $Pr[Detected] - Pr[False\ Neg]$ or

(ii) The *Consequence* amounts.

There are a variety of ways that this may be achieved:

1. Increasing the frequency of inspections/measurement will increase the quantity$(Pr[Detected] - Pr[False\ Neg])$ and therefore also improve the incentive relationship. The costs of doing so are a combination of the direct costs of more inspections/measurement and the increase in the incentive costs because a higher frequency of inspection will lead to more false-positive occurrences.
2. An alternative may be to increase the *Consequence* associated with a measurement indicative of non-compliance.[4] In the presence of imperfect measurement there are 'incentive costs' from doing this.
3. In the presence of improvements in the available technologies for measuring behaviour it may be possible to increase $Pr[Detected]$ or reduce $Pr[False\ Neg]$ through the use of these better technologies without increasing the direct costs and/or potentially reducing the incentive costs.
4. Additional sources of information about behaviour (i.e., that allows the policy to better distinguish compliant and non-compliant behaviour) may also allow low-cost opportunities for improving incentives and/or reducing the overall direct and incentive costs associated with a policy.

3.1 Hypothetical example — Hypoanimals

For the hypothetical hypoanimals pathway, incentive problems were diagnosed, acknowledging that:

1. there seem to be significant profits to be earned from avoiding regulatory requirements for importing hypoanimals;
2. there are significant human and animal health risks/issues to be addressed (spread of SICK; abuse of hypoanimals along pathway);
3. delegation of import protocols to offshore agencies and importers (put in place to minimise human/animal health risk domestically) is problematic because of:
    a. potential for sophisticated gaming/avoidance behavior by suppliers and importers;
    b. difficulty in measurement and verification of behaviour – lack of oversight of the behaviour/actions of suppliers, overseas certifiers and importers; and

[4] In many policies there may be a limit to how large a consequence can be credibly imposed.

c. enforcement – cannot punish entities (particularly o/s operations) when discovered.

Introducing additional hypothetical detail allows the scope of the problem to be framed economically around four typical issues related to delegation:

1. *Measurement* – The biosecurity agency cannot currently observe/verify the actions of key entities on the import supply chain. In particular, the entities located overseas that are responsible for meeting our biosecurity requirements.
2. *Penalties and rewards* – Penalties are available but can only be levied on Australian-based importing operations — in the hypothetical case study the importing operations are based-offshore. Further, penalties have seldom been applied and may not be credible in the eyes of the relevant entities.
3. *Identification* – It is difficult to identify stakeholders upon whom rewards and penalties could be applied. Many of the entities responsible for risk management actions are located (by design) overseas and cannot be readily penalised through regulation. It is also difficult to identify local importers for the purposes of applying penalties/incentives.
4. *Behaviour* – Sophisticated and deliberate behaviour to avoid regulations. This includes collusion by labs/veterinary clinics for falsification of certification.

The process of determining available options and opportunities across 1-4 requires a combination of expertise across:

- incentives/incentive design;
- the science around the risks and managing risks on the pathway;
- details of the pathway; and
- the regulatory environment — what are realistic policy levers that can be implemented/changed?

Examples of incentive design approaches for hypoanimals

There are significant challenges for addressing incentives on this pathway. The first observation about the hypoanimal delegation process (the current approach) is that there are serious consequences for Australia if delegated responsibilities are not implemented. The second observation is that it is difficult for the principal (the domestic biosecurity agency) to directly verify the actions of a delegated agent located overseas. In particular, when the delegated agent has a significant monetary motive to avoid the regulation, there may be a wide range of costly avoidance behaviours that may be in their interests (and other third-parties) to circumvent the regulation. The **key challenge** for regulation to overcome is this tension between measuring/verifying risk management behaviour when it is occurring overseas.

The following set of ideas could be part of a potential incentive-compatible solution:

- Identification of entities to whom incentives are applied:
    - licensing of import business and individuals responsible; and

    - registration/pre-import individual identification.
- Measurement/verification:
    - conditions of license allow auditing and oversight by the domestic biosecurity agency into the process/system being used to guarantee compliance;
    - development of a test that could show compliance; and
    - examination and quarantining.
- Penalties:
    - posting of a bond that may be forfeited if import conditions are not met;
    - value of license/registration for importing hypoanimals creates an ongoing interest in that license/registration not be revoked;
    - credible fines/penalties; and
    - more stringent importing requirements in the future.
- Behaviour:
    - introduce the likelihood of detecting fraudulent certification via random checks or independent verification through audits.

3.1.1 Proposed incentive-compatible mechanism for the hypoanimal pathway

The solution proposed below is one of several potential solution mechanisms related to identification, measurement, penalties and behaviour that have been discussed for this hypothetical hypoanimal pathway.

Approach using licensing

Essentially the mechanism auctions off the right to import hypoanimals to an Australian - owned and operated entity whose adherence to biosecurity rules can be effectively monitored. Entities secure the right to import via a bond. Penalties/rewards can be applied to that entity, and the right to import can be removed when non-compliance occurs.

The broad components of a mechanism proposed (under the circumstances described above) include the following:

1. restrict hypoanimal importers to a small number (a minimum of 3) of Australian - owned and operated hypoanimal import businesses who can be trusted:
    a. restricting the number of rights (licenses) reduces the monitoring and verification problem; and
    b. Australian owned should ensure that non-compliance can be punished.
2. set out the protocols that must be followed when importing hypoanimals:
    a. set out the steps in a sequence; and
    b. set out the documentation and verification process to be used.
3. set out the legal and financial model required for import businesses:
    a. this will identify the specific entity/person that will carry non-compliance risk.
4. set a bond to be lodged by each import business and the process for holding the bond.
5. identify the punishment regime to apply for non-compliance:

   a. the severity of punishment must reflect the severity of impact from non-compliance.

6. prequalification – Call for expressions of interest from Australian owned businesses:
   a. the EOI documents how each proponent would meet the import protocols, legal and financial requirements set out in 2.a, 2.b, 3.a, and 4.
7. hold an auction in which pre-qualified proponents bid for the *rights/licenses* to import hypoanimals:
   a. need to design the auction for this purpose;
   b. need a minimum of three rights/licenses to facilitate competition; and
   c. revenue from the auction goes back to Government.

Because the mechanism described above restricts competition (i.e., to reduce the burden of monitoring and verification – point 1 above), winning firms will earn super-profits (rents) from importing hypoanimals. An auction will 'cream-off' some of the super-profits (like a resource rent in the minerals sector) that can be used to fund (partially) the monitoring, verification and other administrative processes created by the hypoanimals program.

This conceptual mechanism addresses the incentive problem because the rights to import hypoanimals will be lucrative, for the reasons mentioned above.

Additional input from departmental experts is still required to understand how the mechanism overcomes the measurement/verification issue — how well would auditing pre-approval of capabilities through licensing work on this pathway?

To proceed further, additional resources would be required to develop the detailed incentive-compatible solution for the hypoanimal pathway. This process would follow the process outlined in the following sections.

4 Design – Applying Incentive Design

This section provides a high-level overview of developing incentive-compatible interventions. It is applicable in the following situations:

1. developing one single intervention that can be regarded as 'the best' in terms of its incentive properties; and
2. choosing between several incentive-compatible policies.

In either case, the best policy will not only be incentive-compatible but will also be economically efficient. The best policy will be the one that achieves the biosecurity outcome — usually ALOP — at lowest cost.

The are 4 steps to applying incentive design:

Step 1 determine a criterion to evaluate and decide between alternative policies (**Part a**);

Step 2 develop policy alternatives (**Part b**);

Step 3 use the Diagnostic and Economic Framing steps to determine whether each policy alternative is incentive-compatible (**Section 2**); and

Step 4. evaluate and choose amongst the incentive-compatible policies using the criteria chosen in **Part a**.

Part a Decide on criteria to evaluate alternatives

To decide on criteria by which to evaluate alternatives, the policy officer should ask the following question:

Can one readily attach a monetary value to the risks?

If 'no': the criterion for the regulator is to maximise the value to Australia from enabling trade in goods/services on a given pathway subject to achieving an acceptable level of protection from the biosecurity risks.

If 'yes': an alternative criterion may also attach monetary valuations to the biosecurity risks and state the objective as maximising value from enabling trade on a given pathway where the monetary value of the risks is weighed against the value created from the trade of goods on the pathway.

Part b Develop incentive-compatible regulation options

There are a wide range of ways policies across the biosecurity system. The nature of the goods, risks, pathway participants, available sources of information and measurement, range of behaviours that are possible vary greatly from pathway to pathway. As such, there is little scope to provide a prescriptive step by step methodology to arrive at an optimal intervention/policy for any pathway. Rather, the steps are designed to guide a policy maker through a process of design. In practice it is expected that a combination of pathway specific knowledge/expertise and economic framing is required to create efficient and incentive-compatible policies on any given pathway.

We frame the development of policy alternatives in terms of determining the set of activities to delegate to outside parties versus to those in-sourced/conducted by the biosecurity agency (the department). There is a trade-off between efficiency gains from delegating specific activities to external entities and the need for the department to monitor and provide incentives for those parties to conduct these activities in a way that is consistent with Australian biosecurity objectives.

Pathway specific knowledge/expertise is essential for determining what is both feasible on these dimensions and evaluating potential gains from various alternatives.

Step 1. Develop Internal Risk Management Benchmark

A relevant benchmark is whether and how the department can manage the biosecurity risk internally. The first step is to determine whether this is possible and the scale of the costs involved if the risks were managed internally:

- Is it possible for the department to manage the risk internally?
- What are the ways the department can do this?
- Is there a least-cost method for the department to do so?
- What are the costs to the department or other pathway participants if this approach were implemented?
- Do the potential costs make this alternative infeasible?

The output of this step may be an approach to managing the risk without reliance on outside parties. Such an approach may or may not be possible whilst also allowing trade on the pathway. If it is not possible to manage risk internally, reliance on outside parties and the need to design incentives is essential for allowing trade to occur on a pathway.

Step 2. Delegating Risk Management Activities

The second step is to determine the types of activities that, if undertaken by external parties (non -department entities), can manage the biosecurity risk and offer benefits relative to managing the risk internally, as determined in step 1. There are a number of sources of advantage from having external entities undertake risk-management activities. These include:

- lower cost – outside parties may be better able to undertake risk-management activities because of expertise, capabilities etc;
- feasibility – some activities, such as those that are a part of a production process, can only be undertaken by external entities that are producing a good; and
- reduced risk – certain risk-management activities must be undertaken prior to arrival in Australia and so are undertaken by entities located off-shore.

On many pathways there will be significant benefits from delegating activities to outside parties. The extent to which these benefits can be realised in practice are determined by whether a policy can be created to make it incentive-compatible for outside parties to undertake these activities in a way consistent with Australia's biosecurity objectives.

Step 3. Measurement and Policy Levers

Central to the design of incentives is the ability of the regulator to measure/verify/acquire information about the behaviour of the regulated individuals/entities.

The scope for providing incentives to external parties to manage a biosecurity risk is therefore dependent on the sources of measurement of their actions and the policy levers available to affect the outcomes that these external parties care about.

The third step is to determine what is available along these two dimensions around which an incentive-compatible policy can be designed.

Step 3a. Sources of measurement

The following questions should be answered:

- For the activities identified in step 2 what are the potential sources of information or measurements that can be used to determine whether the activities have been carried out in a way that is consistent/inconsistent with managing a biosecurity risk?
- How well and easily can the regulator determine whether individuals are engaging in behaviour that is consistent with the policy (thereby maintaining an acceptable level of risk) or inconsistent with the policy (creating an unacceptable risk) — i.e., compliance vs non-compliance?
- What are the technologies and procedures that the regulator uses to check compliance? These are what allows the regulation to connect the decisions of the regulated entities with potential outcomes that are influenced by the regulation.

The most elementary of these sources of information are inspections that occur at the border upon arrival. An inspection can reveal information that the goods pose an unacceptable biosecurity risk and a corrective action is required to manage the risk. For example, the identification of a foreign pest in shipment of agricultural or food products is more likely to occur in shipments that have not been subject to biosecurity practices consistent with preventing this. One way this information is used in practice is to determine appropriate corrective actions to manage the risk such as destroying the shipment or a treatment. In addition to managing the risk, this type of information may be used to design regulations that provide incentives for compliant behaviour.

There are potentially multiple sources of information, the cost and precision (how revealing is it of non-compliant behaviour) of these sources will determine the most efficient mix of information sources to design incentive-compatible regulation. In many instances there will be a trade-off between cost and precision — **the more precise sources of information may be more expensive to obtain**. For instance, in-water inspections of a ship's hull and niche area may be a precise source of information about whether a ship operator has been following compliant biofouling procedures, but it is also expensive to undertake in time and money. Hence, it will not be the most efficient source of information in all instances and may be used sparingly in the regulation as a result.

Step 3b. Identify policy levers

The second element is the identification of potential policy levers for affecting outcomes that the relevant decision-makers care about (i.e., their objective from earlier which in many cases is their long-term profitability).

Potential levers may be direct monetary outcomes — e.g., levies/fines or pass through of costs associated with managing a risk; or indirect measures — e.g., faster/slower times for a shipment to clear the border or changes to future arrangements for an importer to reward/punish historically good/poor performance (e.g the Compliance-Based Intervention Scheme; Rossiter and Hester, 2017, Rossiter et al., 2019).

A non-exhaustive list of policy levers that are used in practice include:

- **Monetary outcomes** are a direct means to influence the profits of a regulated entity. This may occur as the result of fines, levies or the pass-through of costs associated with treatment/disposal/remedial actions for managing a biosecurity risk. These monetary consequences need not always be viewed as a "punishment" per se, as relative outcomes are what is important from an incentive point of view. For instance, reducing the amount of a levy because of information of behaviour that reduces/minimises a biosecurity risk is a source of "reward."
- For some goods the amount of **time spent clearing the border** affects the quality of the product and eventual price an importer may receive from selling the goods. For example, the quality of cut flowers deteriorates over the course of days and so reducing the number of days a consignment of flowers takes to clear the border is an outcome that is valued by an importer. The efficacy of this policy lever will vary with the pathway characteristics as different goods will be more or less sensitive to the time taken to clear the border.
- A potentially powerful source of incentives are policy levers that influence the **nature of future regulatory arrangements for importers**. In the near term there may be limits to the scale of the action a regulator may take (it can only reduce the delay on a single shipment to some minimum time, or there may be limits to how much a single levy may be reduced/increased etc). When the regulator can also affect how an importer is treated in future arrangements this may give it greater flexibility to reward or punish compliant/non-compliant behaviour and thereby provide more effective/stronger incentives.
- How the regulator uses the information it collects may be of value/concern to an importer or supplier. For instance, **sharing information** indicative of a good/poor behaviour of a particular supplier with foreign counterparts may affect how that foreign regulator treats that supplier in that country. Alternatively, a record of good biosecurity performance may be valuable to some end consumers either because good biosecurity practices are also indicative of a higher quality product (e.g., goods that are consistently free of pests/diseases when they arrive in Australia may be more valued by end-consumers and reason a premium). In these cases, sharing information with relevant parties or making it public may be a source of incentives for improved performance for suppliers/importers.

- Finally, in cases where an individual has broken the law and then the legal system may be used to bring **criminal or other charges**.

Step 4. Create Policies

The final step is to create policies that link the available sources of measurement to policy levers/outcomes that external parties care about in a way to create incentives for those parties to act in ways that are consistent with managing the biosecurity risk.

Policy forms

The policy may take a wide variety of forms depending on the unique characteristics of a pathway. Here we outline three types of policy alternatives: *static, dynamic* and *menus*.

Static

Static schemes are the simplest incentive structures. A static incentive scheme does not change over time and so there is no connection between a regulated entity's history of performance with the type of regulation they face. The incentives in these schemes are entirely determined through one-off interactions with the regulator. For instance, a static incentive scheme may measure/obtain information about whether a given shipment meets Australia's biosecurity standard and determine an outcome (e.g., allow entry when it does and destroy goods, impose a monetary fine etc. when it does not) based solely on the information about that individual shipment.

Provided that the information is sufficiently precise and the relevant decision-maker cares sufficiently about the differences across the potential outcomes then this will induce incentive-compatible behaviour. The attraction of these schemes is that they are simple to understand for the regulated entity and by virtue of their simplicity also typically robust to manipulation (or readily checked to be robust).

Dynamic

Dynamic regulation changes over time based on the historical performance of a regulated entity. For instance, historically good (resp. bad) biosecurity performance results in lower (higher) likelihood of inspection in the future or faster (slower) processing time for future shipments (Figure A. 9). These types of schemes are appealing because they offer a larger set of potential outcomes for the policy to influence and so have greater scope to provide strong incentives for compliant behaviour. A potential drawback of this type of scheme is that regulated entities may adjust their behaviour over time (in potentially complex ways) to manipulate the regulation to their own benefit. Hence, ensuring that these schemes are incentive-compatible and not subject to manipulation is more demanding for the regulator.

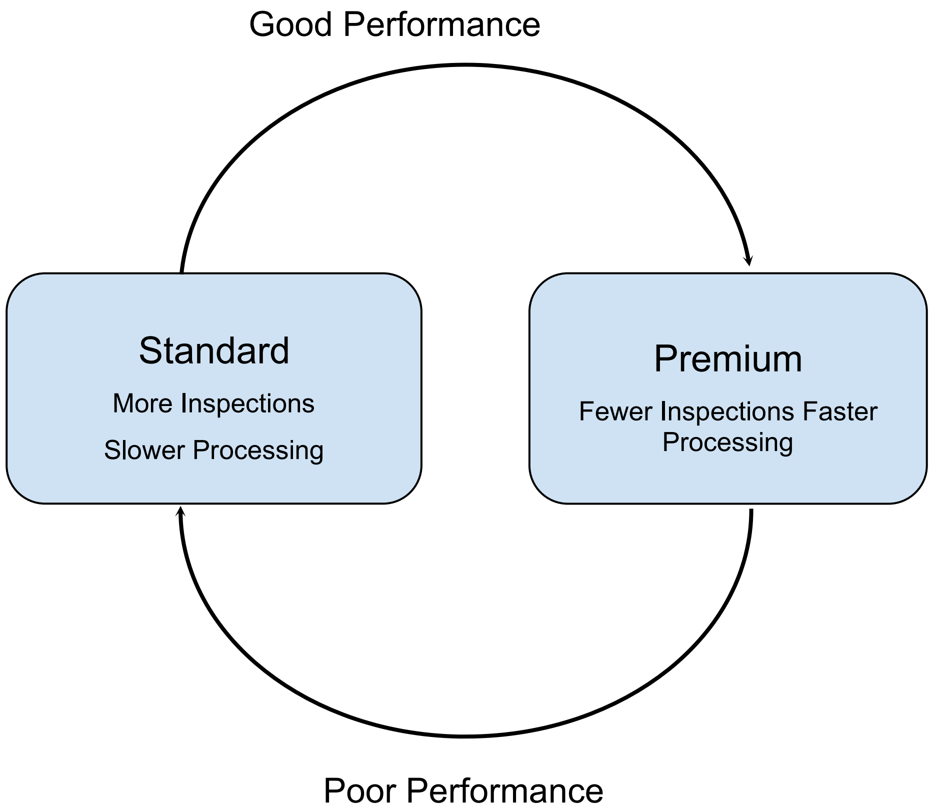

Figure A. 9. Representation of how regulatory changes evolve over time under dynamic regulation, adapting to the historical performance of the regulated entity

Menu

A menu of regulations offers the regulated entities a choice of regulatory schemes. The reason to offer a menu of regulations is that the most efficient form of regulation may be related to a characteristic of the regulated entity (e.g., some suppliers/importers have very good biosecurity practices while others do not). These characteristics may be known to the regulated entity but not the regulator (e.g., suppliers/importers know how good their biosecurity practices are but the regulator does not know). In these cases, a well-designed menu of choices by the regulator, can allow "self-selection" of some entities into a form of regulation that is more efficient for them. The appeal of this class of schemes is that the regulator can take advantage of "self-selection" to better match regulation to characteristics of the regulated entities (Figure A. 10).

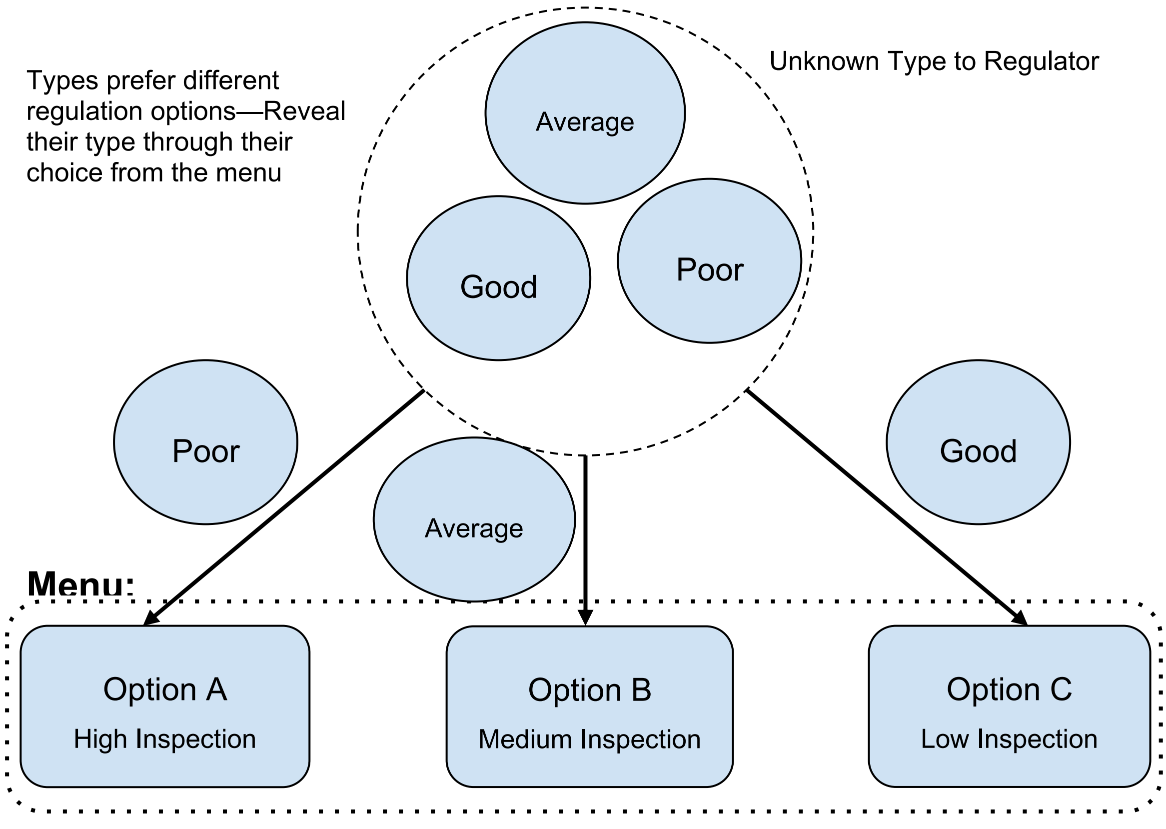

Figure A. 10. A well-designed menu of choices allows types (to self-select into more efficient regulatory frameworks, enabling a better alignment with their characteristics.

Additional policy considerations — Are decentralised approaches available?

These approaches may at times only partially address incentives and so may be used in conjunction with policies developed in the earlier step. Options include *third party certification*, *information provision* and the use of *private risk markets*.

Third Party Certification

Campbell et al. (2021) describes conditions under which third party certification may offer equivalent assurance that goods meet Australian biosecurity standards. A policy can utilise this source of information in its design to provide incentives. A simple version of this is that any products or goods that obtain the certification are deemed to meet the relevant biosecurity conditions. The benefit of this type of scheme is that the third-party certifier is likely to be more efficient at measuring/verifying/monitoring of compliant/non-compliant behaviour.

Information provision

The information that the department collects about biosecurity performance may be valuable to consumers of those products. In particular, good biosecurity performance may be indicative of a high-quality provider of goods and so consumers will pay a price premium for goods from those importers. Situations where consumers would value the information that department collects (or could collect at low cost) may offer opportunities to improve incentives for biosecurity performance by making it publicly available or salient to consumers through a good biosecurity performance certification. In these instances, the outcome that is helping to create the incentive is the price consumers pay. The attraction of this type of scheme is that the improved biosecurity performance only requires the regulator to make information available to consumers (this is likely to be relatively low cost).

Private risk markets

Biosecurity is a class of risk that arises from the inward movement of goods and people. In other domains of the economy where specific conditions apply (see Berliner, 1982) risk is managed by creating markets for risk. In Stoneham et al. (2021) it was shown that markets for biosecurity risk are missing because risk-creators (i.e., importers) are not exposed to the financial losses they create — not because biosecurity risk is uninsurable according to the criteria outlined by Berliner.

The advantage of creating a market for biosecurity risk is that markets price risk efficiently based on the principles of: i) risk pooling — i.e., spreading risk across many importers dissipates the unsystematic component of risk; and ii) actuarial pricing creates an incentive to mitigate high-risk activities.

These principles of risk market design reveal the efficient price of risk thereby creating an incentive for importers to discover lower risk pathways/goods and create a pool of funds needed to support the biosecurity system and fund responses to incursions when they arise. The specific characteristics of a market for biosecurity risk are outline in Stoneham et al. (2021). A key focus of our system pathway overhaul component of the project is to adapt the principles used to design private risk markets to the biofouling domain of biosecurity (see Appendices D to G).

When it is possible to use private risk markets it may be beneficial to do so because much of the implementation is undertaken by insurance companies that have expertise and a profit motive to do this efficiently. The role of the government is more limited in scope but will still have some responsibilities, for example, in implementing a mandate for importers to purchase insurance.

Part c Evaluate against criteria

It may not always be possible to reliably generate some absolute measure of the economic performance of a policy. As such, one practical approach is to make a relative comparison of each alternative to one another. A natural baseline for this type of exercise is to use the best internal (no delegation) policy for managing the risk and compare alternative policies that delegate some actions to outside parties to this baseline. In making these comparisons the policy maker must assess the relative benefits from delegating activities against the associated costs of managing the incentives of external parties to undertake these activities.

Sources of Benefits

What are the benefits/efficiencies that can be gained from delegating under each policy relative to managing the risk internally? Some of the potential sources of efficiencies include:

- greater capacity of outside parties to undertake the tasks because of superior information and expertise;
- better/direct incentives for minimising costs of completing the tasks;
- risk mitigation — to the extent the activities can be conducted overseas it may limit some types of the biosecurity risks from entering Australia; and
- some entities may be undertaking the tasks as part of their business in the absence of regulation so the incremental costs (in addition to costs that they would otherwise incur) are negligible (e.g., third-party certification, biofouling management software).

Sources of Costs

There are two types of costs from the need to provide incentives:

- costs associated with the monitoring, measurement and information collection activities. These costs are the resources required by the department to monitor/measure behaviour on the pathway. Even if some or all of these costs are passed on to pathway participants, they affect the net benefits derived from trade on a pathway and are important to account for.
- costs associated with imperfect measurement. The nature of these is described in Section 3 of this manual. These derive from a policy imposing a penalty or other consequence when it falsely detects behaviour that is inconsistent with the intent of the policy (false negatives). This occurs because most sources of information or measurement are not perfectly precise and the associated costs of it become more severe when these sources are less precise.

5 Testing and Refining

Best-practice regulation suggests that the final step, before putting an incentive-compatible regulation into practice or into a field trial, is a robustness check of the proposed regulation. This robustness check can ideally take the form of a field experiment, which allows for rigorous testing of the policy's causal effects on behaviour in a real-world setting. For example, in the current context, a new biosecurity policy could be piloted in one port or with a specific group of importers, with their responses compared against a randomly assigned control group, thereby allowing for clear causal attribution prior to broader implementation.

There are 3 dimensions along which to check:

1. robustness to manipulation;
2. checking for unintended consequences; and
3. confirming whether behaviour in an economic lab experiment is consistent with the purpose of the regulation

1. Robustness to manipulation

Can the regulation be manipulated?

Ideally, all those regulations considered in the previous step would be immune to manipulation by virtue of being incentive-compatible. However, in the design of the regulations, one may not have been aware of actions available to the decision-maker to avoid/manipulate the regulation. If this is the case, then the regulation will not have taken these into account in its incentive- compatible design and may be susceptible to manipulation.

The policy creator should put themselves in the shoes of the individuals being regulated and ask how it would attempt to avoid/manipulate the regulation. This step will likely benefit from a range of inputs from different people in the department with a range of expertise (e.g., biosecurity agency staff in the Compliance Division would naturally have some expertise/knowledge for thinking through this issue).

2. Checking for unintended consequences

Does compliant behaviour, as a result of the policy, change other behaviour or divert resources from other activities that then create new risks?

Putting very strong incentive structures into place can create unintended consequences. Unintended consequences may occur when a decision-maker diverts time/effort/resources away from other activities in order to engage in the compliant behaviour that is the focus of the policy. When this occurs, it can create new risks. The policy creator can engage with relevant stakeholders on the pathway to explain the proposed regulation and understand how they anticipate it will affect behaviour more broadly.

3. Economic lab experiments

Do people respond to the regulation in a manner that is consistent with the intent of the regulation in an economic laboratory?

An important innovation in the last 30 years has been in the development and use of economics laboratory experiments for testing human behaviour. These types of experiments can be used in the context of incentive structures to test whether actual behaviour differs systematically from how it is assumed in the design of the incentive structure.

An important assumption, used in the design of any incentive structure concerns how people will respond to a particular set of incentives. Commonly, it is assumed that individuals:

i. are highly sophisticated in how they process information and make choices;

ii. have narrowly defined preferences that value outcomes that benefit themselves but place little value on how an outcome affects others; and

iii. are sophisticated in not only their own strategic reasoning but are also confident other people are similarly sophisticated in theirs.

These are strong assumptions because nobody exhibits behaviour that is perfectly consistent with these assumptions in all situations. The utility of these assumptions is that they are a robust predictor of human behaviour in many circumstances and provide a benchmark against which to measure actual behaviour. In instances where behaviour deviates systematically from these assumptions, varying some aspect of an environment that moves behaviour back in the direction of the benchmark tends to reveal which assumption is not being met.

While economic theory and intuition provide predictions about how regulated entities are expected to react under different regulations, economic experiments were constructed as a test-bed to measure the effects of different experimental treatments on the behaviour of participants. Importantly, experiments can examine how incentive and information structures may interact to change decision-making of experimental subjects. For example, DAFF and CEBRA used economic experiments to design and test incentive-compatible protocols for pre-border regulation (Rossiter et al., 2018). The aim of the project was to assess the incentives inherent in compliance-based inspection protocols and to select key parameter values that would encourage importers to reduce the likelihood of biosecurity risk material (BRM) entering Australia (Rossiter et al., 2016).

Imposing regulatory changes without carefully considering stakeholder responses could introduce inappropriate incentive structures for compliance and deliver unintended policy consequences, potentially undermining the maintenance of Australia’s high biosecurity status.

6 Scaling

Implementation of the intervention into practice or via a field trial occurs once any final refinements are made. It is important to measure the change in behaviour as a result of a policy and to quantify the benefit that it has created (e.g., a reduction in costs, improved risk management etc.).

Part of policy implementation should therefore include how to evaluate the impact of the policy on behaviour and quantify its benefit. These anticipated effects of the policy will guide the data types and sources that should be tracked or collected upon the policy implementation and subsequently used to inform the policy evaluation. We describe some guiding questions for developing a strategy to achieve this.

Developing a hypothesis for assessing the effect of the policy on behaviour

What are the changes in behaviour that we anticipate being able to observe and how will the policy affect the market that the regulated entities participate in?

- What are the anticipated changes in the behaviour of firms or individuals from pre- to post-policy implementation?
    - Better compliance performance?
    - Changes in suppliers or source countries used?
    - Changes to the volume/value/types of goods being imported?
- Changes in the characteristics of firms or people participating in the relevant market.
    - Are there more/fewer firms engaging in trade?
    - Have the firms engaging in trade changed in a systematic manner?
- Changes in prices or quantity of products in the market
    - Will the volume of goods and/or value of goods on the pathway change?
    - Will the prices of goods change as a result of the policy?
    - Are there anticipated changes in related markets (this may include domestic markets for similar products)?

Quantifying the improvement from the policy

A well-functioning policy should ensure that Australia achieves ALOP (or alternative objective) on a pathway while minimising the compliance costs of meeting the policy. Thus, there are two relevant dimensions: biosecurity risks and compliance costs, along which a policy may benefit Australia. This implies that the evaluation of the policy should quantify:

- changes in biosecurity risk; and
- changes in compliance costs.

The anticipated effect of the policy will guide the data types and sources that should be tracked or collected upon the policy implementation and subsequently used to inform the policy evaluation.

Policy evaluation

The ideal approach to policy evaluation is a well-designed field experiment/trial that allows a straightforward comparison between a treatment and control group to infer the effect of a policy on behaviour (see List and Rasul, 2011 for an overview of this methodology). This may not be possible in all cases. In the absence of such a field experiment then applying modern micro-econometric techniques for policy inference is the preferred approach (see Angrist and Pischke, 2009 for an overview of these techniques).

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Appendix B: Incentive Diagnostic Tool Template

Pathway description

[Pathway] *Provide some context to the pathway, the proposed/current intervention, including examples of non-compliance if any. For example, see Box 1 in the tool's Manual*

Complete this table as completely as possible for the pathway under analysis. Note, answers may include 'unclear' or 'unknown'. Example answers are given in Sections 2.1-2.5 of the tool's Manual.

No.	Question	Answers:
Step 1. Participants and Compliance		
1.1	Who are the stakeholders on the pathway (e.g businesses, end-consumers, regulators etc.)?	• • •
1.2	What does each entity (in 1.1) do to manage the biosecurity risks?	[Stakeholder 1] • [Stakeholder 2] •
1.3	Does each stakeholder understand (are aware of) their responsibilities under the intervention?	Yes/no/unclear/unknown: [reasoning]
1.4	What are the costs of complying with the biosecurity regulations?	[$, and explanation]
Comments/Notes		

Step 2. Relationships		
2.1	What are the economic/regulatory relationships between the entities detailed in step 1?	[Participant 1 to Participant 2] •
2.2	Are the relationships repeated/ongoing? If yes, which?	Repeated/ongoing relationships: •
2.3	Are there financial transactions between the entities? If yes, explain.	Yes/No: [explanation] •
2.4	If a product or service is being supplied/purchased, is the quality relevant/observable to both parties?	Yes/No: [explanation]
Comments/Notes		

Step 3. The nature of (potential) non-compliance		
3.1	What are the non-compliant behaviour(s) and which stakeholders are responsible for these?	[List non-compliant behaviours] [responsible stakeholder]
3.1a	• Are these non-compliant behaviours concentrated amongst a subset of these stakeholders?	Yes/No
3.1b	• Is coordination across multiple decision-makers required to successfully (derive benefits from) avoid the intent of the policy?	Yes/No
3.2	What are the benefits of non-compliance and who do these directly accrue to?	Benefits: [$] Accrue directly to:
3.2a	• Are the benefits from avoided costs of meeting the policy/regulatory requirements significant? • Do they outweigh the costs of meeting the policy	Yes/No [explain]
3.2b	• Are the benefits derived from higher prices?	Yes/No [explain]
3.3	Are the benefits or cost savings readily transferable between different entities?	Yes/No
3a	• Can the benefits or cost savings be dispersed from the entities that directly receive them to the entities that are	Yes/No [explain]

	responsible for non-compliant behaviour?	
3b	• If so, what is the nature of the transfer?	e.g., Financial payments
Comments/Notes		
Step 4. Measurement		
4.1	What is measured by Australia's biosecurity agency about compliant/non-compliant behaviour and how frequent and precise are these measurements?	[e.g., Inspection of documents] •
4.2	What is measured by the OS Competent Authority (or other relevant parties) about compliant/non-compliant behaviour and how frequent and precise are these measurements?	e.g., Inspection of documents •
4.3	Do the relevant entities anticipate that these measurements are being made/observed?	Yes/No
4.3a	• Do they approximately understand the frequency/precision of the measurement?	Yes/No
Comments/Notes		
Step 5. Consequences		
5.1	What are the potential consequences from measurements consistent with non-compliance for the source(s) in Step 4 and to whom can these be applied? • When are these penalties applied in practice or what is the trigger for these to be implemented?	e.g., Australian consumer • If the animal is identified as posing a risk then it may be euthanized.
5.2	Are the consequences credible/understood by the relevant entities?	Yes/No: [explain]
Notes		

Step 6: Construct decision-maker's trade-off(s)

Step 6 involves using the information derived in Steps 1-5 to understand whether the decision-maker will comply with the proposed or existing intervention, or not.

A stylised depiction of a decision maker choosing whether to engage in a strategy to avoid (Avoidance) or comply with the rules and processes created by the biosecurity authority (No-Avoidance) is illustrated below.

In a nutshell, the decision-maker will compare the costs and benefits of compliance with those for non-compliance. This is the decision-maker's 'trade-off'. This trade-off needs to be evaluated to determine whether the intervention contains the *right* incentives i.e., that the No Avoidance strategy will be the preferred one.

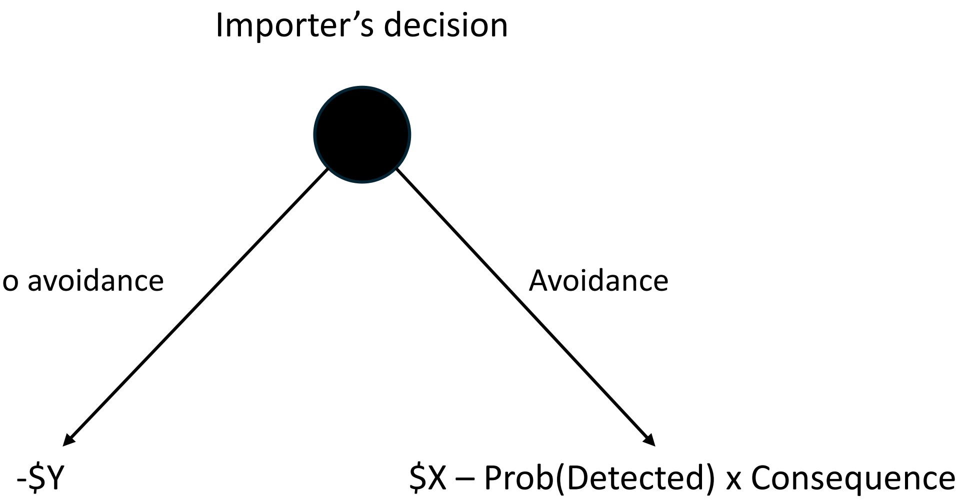


Figure B. 1. Example of decision-maker's trade-off (Note frequency is not included in this case)

To construct the decision-maker's trade-off, proceed as follows:

Step 1. Determine the following values:

- ***Y**:* the cost ($) of compliance with the biosecurity intervention (i.e., the cost of undertaking a particular treatment in order to be compliant);
- ***X***: the amount gained ($) from avoidance (e.g., by skipping a compliance action that involves time delays, products may arrive faster or in better condition and thereby sell at a premium);
- ***Detect*****:** the probability that non-compliance will be detected, (e.g, inspection should identify non-compliance with a probability of *Detect*);
- **Frequency[11]:** the frequency that a good/shipment is inspected for compliance; and
- ***Penalty***: the penalty/consequence ($ or $-equivalent) that is incurred as a result of detecting non-compliance (e.g., the import may be destroyed and/or the importer may pay a fine, or the shipment may be delayed and goods deteriorate in quality).

Step 2. Determine:

- the net benefit from Avoidance: $X - Frequency \times Detect \times Penalty$
- the cost from No Avoidance: $-Y$

Step 3. Check whether importers have an incentive to choose No avoidance/compliance (no incentive issues are present) or Avoidance behaviours/non-compliance (incentive issues are present). For importers to comply with biosecurity regulations, the benefit from compliance must outweigh the expected benefits of non-compliance; i.e., **check**:

$$Frequency \times Detect \times Penalty > X - Y$$

Step 4. Form a conclusion about the existence of incentive issues on the pathway:

- No issues: exit tool (existing policy) or **Section 5** or **Section 6** (new policy)
- Incentive issues, Use Case 1: go to **Section 4**
- Incentive issues, Use Case 2: go to **Section 3**

Conclusion:

[11] Note that the *Frequency* that a good/shipment is inspected for compliance can be excluded for simplicity.

Appendix C: Incentive Diagnostic Tool — Ballast Water (June 2025)

Pathway description
Ballast water, on vessel with Ballast Water Management System (BWMS), aiming for D-2 compliance as acceptable biosecurity risk for discharge.

Complete this table for the pathway under analysis. Example answers are given on pp. 11-19 of the tool's Manual

No.	Question	Answers: Ballast water
1. Participants and Compliance		
1.1	Who are the participants on the pathway (e.g businesses, end-consumers, regulators etc.)	• Vessel owners, shipping agents, crews. • International Governments, Class Societies as issuers of type approvals for BWMS. • DAFF BWU, AMSA.
1.2	What are the actions that each participant in (1) undertakes to manage the biosecurity risks?	[Administrations] • Issue type approvals [Manufacturers] • Build and have systems type approved [Class societies] • Survey vessels to ensure seaworthiness and compliance with international regulatory requirements [Vessel owners] • Need to install a type approved BWMS [Shipping agents] • Cargo/journey planning and freight costing [Crews] • Control vessel including operation, maintenance and monitoring of the BWMS, port operations [DAFF] • Compliance with Part 5 of Biosecurity Act (including D-2 standard, BWMP adherence etc) [AMSA] Compliance with vessel/survey standards
1.3	Does each participant understand (are aware of) their responsibilities under the intervention?	Yes/No: Mixed Administrations should follow the BW Code but do not always.

		Vessel owners know they need a type approved BWMS but may not differentiate between legitimate and problematic type approvals. Class societies have variable interpretations of what a ‘type approved’ BWMS comprises. Some BWMS on surveyed vessels may not be properly type approved. Shipping agents use vessels appropriately surveyed but do not have adequately detailed information about whether BWMS are properly type approved. Crews have mixed awareness of the convention and operation and maintenance of BWMS. DAFF regulates ballast water; the main requirement is that any discharged ballast water meets the D-2 standard.
1.4	What are the costs of complying with the biosecurity regulations?	[$, and explanation]
Notes **Understanding of the system is still poor and emerging at most levels apart from DAFF.**		
2. Relationships		
2.1	What are the economic/regulatory relationships between the entities detailed in step 1?	[Administrations to Class societies] • Indirect only. Administrations to manufacturers • Manufacturers rely on Administrations to type approve ballast water management systems • All levels of the system rely on administrations to properly type approve ballast water management systems Manufacturers to vessel owners • Cost-profit motive – often cheapest system is chosen • Assumption that ‘type approved’ systems work Class societies to vessel owners • Class societies provide survey services – owners assume surveyed vessels meet standards including type approval for BWMS • Vessel owners rely on class societies to properly survey vessels and approve them as seaworthy

		• Vessel owners have profit-time motives, including consistent on time loading and off loading cargo [Vessel owners to crew] • Profit motive for on-time operations • Efficiency motive to decrease costs • M [DAFF] •
2.2	Are the relationships repeated/ongoing? If yes, which	Repeated/ongoing relationships: ● All relationships are ongoing ● Manufacturers seek type approval for a design only once ● Most vessels have a BWMS installed when manufactured, then replaced at 10+ year intervals
2.3	Are there financial transactions between the entities? If yes, explain	Yes ● Administrations charge manufacturers fees to type approve systems ● Manufacturers sell BWMS to vessel owners/shipyards ● Class societies charge vessel owners fees for surveys ● Vessel owners pay crews ● DAFF charges fees for biosecurity services ● AMSA charges fees for inspections
2.4	If a product or service is being supplied/purchased is the quality relevant/observable to both parties?	No. Understanding of type approval is poor. The cheapest BWMS is often installed. There is an assumption that if a system has type approval that it will work. This is often not the case. The regulators can see results but not operation.
Comments/Notes		

3. The nature of (potential) non-compliance		
3.1	What are the non-compliant behaviour(s) and which entities are responsible for these?	Type approval for BWMS that do not meet standard Improper use of BWMS Improper maintenance of BWMS
3.1a	• Are these non-compliant behaviours concentrated amongst a subset of these entities?	Unclear
3.1b	• Is coordination across multiple decision-makers required to successfully (derive benefits from) avoid the intent of the policy?	Unclear
3.2	What are the benefits from the non-compliance and who do these directly accrue to?	Benefits: Time and ease of operation Accrue directly to: Crews Benefits: Decreased operational cost Accrue directly to: Vessel owner and Shipping agents
3.2a	• Are the benefits from avoided costs of meeting the policy/regulatory requirements significant? • Do they outweigh the costs of meeting the policy?	Mixed Time for crews is significant for meeting deadlines. Actual value of decreased activities/meeting regulatory requirements is marginal to low.
3.2b	• Are the benefits derived from higher prices?	Unclear
3.3	Are the benefits readily transferable between different entities?	No
3a	• Can the benefits be dispersed from the entities that directly receive them to the entities that are responsible for non-compliant behaviour?	Unclear
3b	• If so, what is the nature of the transfer?	e.g., Financial payments
Notes Non-compliance may provide crew time benefits worth <$US10,000		

4. Measurement		
4.1	What is measured by Australia biosecurity about compliant/non-compliant behaviour and how frequent and precise are these measurements?	e.g., Inspection of documents: • Ballast water management plan • Ballast water management certificate • Type approval certificate •
4.2	What is measured by the OS Competent Authority (or other relevant parties) about compliant/non-compliant behaviour and how frequent and precise are these measurements?	e.g., Inspection of documents • D-2 standard
4.3	Do the relevant entities anticipate that these measurements are being made/observed?	Yes At least once testing of ballast water is more widespread they will understand and anticipate it. A trial in Newcastle got the shipping industry peak bodies fairly unhappy fairly fast. So word travels quickly.
4.3a	• Do they approximately understand the frequency/precision of the measurement?	No Even once testing/assessment is more regular the frequency is likely to be only moderately well understood, but there will be high awareness of the possibility

Notes

If sent offshore to exchange and treat or otherwise manage ballast as directed, the cost per vessel will be at least $US15k per day plus $US20-50k berthing and port fees. Total cost is likely to be over $US100k/vessel if directed to leave port and exchange and treat or otherwise not discharge ballast in Australian waters.

5. Consequences		
5.1	What are the potential consequences from measurements consistent with non-compliance for the source(s) in Step 4 and to whom can these be applied? • When are these penalties applied in practice or what is the trigger for these to be implemented?	e.g., Crew • Delay • Potentially fines or demerits Ship owner • Fines and demerits • Delay and increased costs Shipping agent • Delay and increased costs

5.2	Are these credible/understood by the relevant entities?	Yes Cost of delay in particular is very well understood
Notes		

Step 6: Construct decision-maker's trade-off(s)

Step 6 involves using the information derived in steps 1-5 to understand whether the decision-maker will comply with the proposed or existing intervention, or not.

A decision maker confronted with a choice of whether to engage in a strategy to avoid (Avoidance) or comply with the rules and processes created by the biosecurity authority (No-Avoidance) is illustrated below.

In a nutshell, the decision-maker will compare the costs and benefits of compliance with those for non-compliance. This is the decision-maker's 'trade-off'. This trade-off needs to be evaluated to determine whether the intervention contains the *right* incentives i.e., that the No Avoidance strategy will be the preferred one.

To construct the decision-maker's trade-off, proceed as follows:

Step 1. Determine the following values:

- ***Y:*** the cost ($) of compliance with the biosecurity intervention (i.e., the cost of undertaking a particular treatment in order to be compliant).
- ***X***: the amount gained ($) from avoidance (e.g., by skipping a costly compliance action, products may arrive faster or in better condition and thereby sell at a premium).
- ***Detect***: the probability that non-compliance will be detected, (e.g, inspection should identify non-compliance with a probability of *Detect*).
- **Frequency:** the frequency that a good/shipment is inspected for compliance (optional).
- ***Penalty***: the penalty/consequence ($ or $-equivalent) that is incurred as a result of detecting non-compliance (e.g., the import may be destroyed and/or the importer may pay a fine, or the shipment may be delayed and goods deteriorate in quality).

Step 2. Determine:

- the net benefit from Avoidance: $X - Frequency \times Detect \times Penalty$
- the cost from No Avoidance: $-Y$

Step 3. Check whether importers have an incentive to choose No avoidance/compliance (no incentive issues are present) or Avoidance behaviours/non-compliance (incentive issues are present). For importers to comply with biosecurity regulations, the benefit from compliance must outweigh the expected benefits of non-compliance; i.e., **check**:

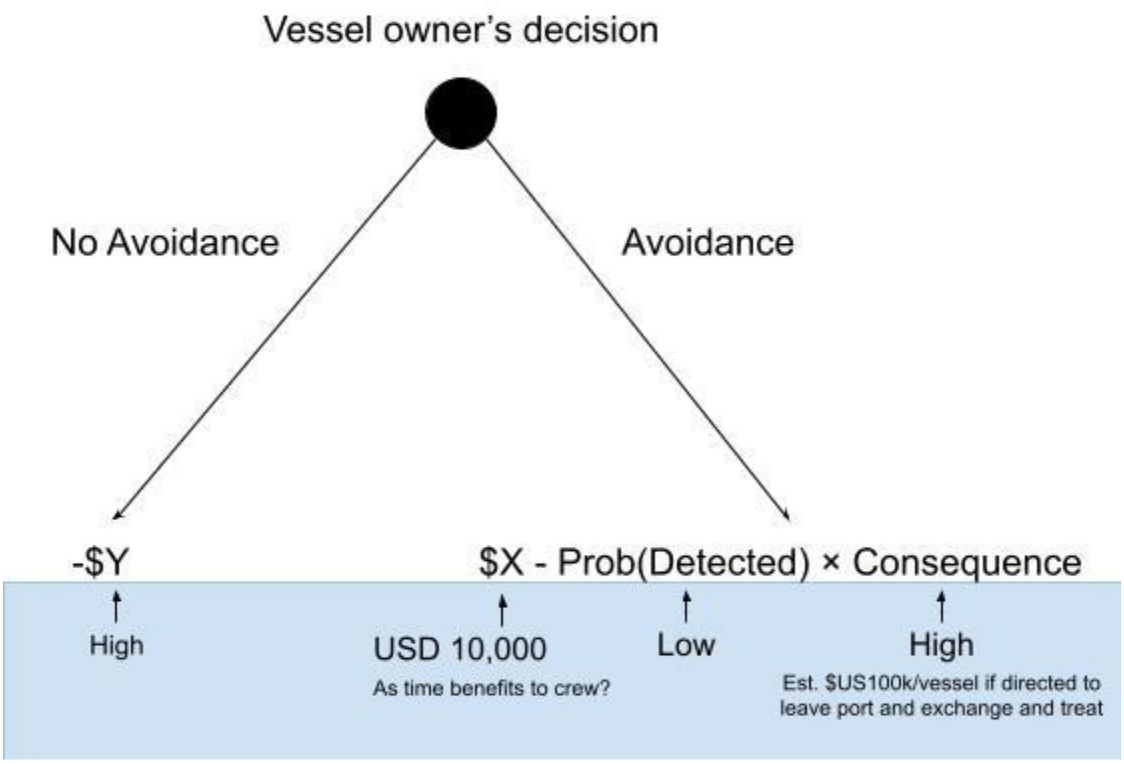
$$Frequency \times Detect \times Penalty > X - Y$$

Step 4. Form a conclusion about the existence of incentive issues on the pathway:

- No issues: exit tool (existing policy) or **Section 5** or **Section 6** (new policy)
- Incentive issues, Use Case 1: go to **Section 4**
- Incentive issues, Use Case 2: go to **Section 3**

Conclusion:

If vessels are caught avoiding ballast-water-management rules the penalties are significant. However, there is currently a low likelihood that vessels are caught avoiding ballast water rules. This means there is likely to be an incentive problem with vessels adhering to ballast water rules given there is more benefit to vessels in not complying compared to complying. If the probability of detection could be increased, along with the frequency of inspection (not shown), then the amount of rule avoidance would decrease.



Vessel owner's trade-off [not yet finalised at time of writing]

Appendix D: Incentive-compatible biofouling mechanism

Milestone 11 Report for CEBRA 21C

Incentive-compatible biosecurity policies – a framework for regulatory design

Case study: A biosecurity risk insurance mechanism

Milestone 11 Report for CEBRA Project 21C

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Table of Definitions

Actuarial pricing: Actuarial pricing is how insurers turn uncertain future losses into a premium. It covers expected claims and running costs and pays for the capital that backs the promise to pay. Note that in actuarial science, 'risk' is shorthand for the uncertain financial liability/exposure that needs to be priced.

Actuarial science: is a field that evaluates financial risks in insurance and finance using mathematical, economic and statistical techniques.

Adverse selection: refers to the challenge of assigning agents with varying risk profiles to contracts where insurance premiums are based on the agent's risk rating.

Alignment problems: the differences that occur between how a principal and agent in an organisation would prefer a particular task to be done. Where alignment problems exist, there are potential gains to both parties from improving the incentives of the agent for undertaking the task.

ALOP (Appropriate Level of Protection): Under the *Sanitary and Phytosanitary Measures Agreement*, World Trade Organization members are entitled to maintain a level of protection they consider appropriate to protect life or health within their territory. Australia's ALOP, as defined in the *Biosecurity Act 2015* (Australian Government, 2015), is expressed as providing a high level of sanitary and phytosanitary protection aimed at reducing risk to a very low level, but not to zero.

Approaches to managing biosecurity risks: under a **centralised approach,** risk mitigation activities — including pre-border initiatives, border controls, and post-border interventions — are imposed by biosecurity authorities, with management decisions based largely on technical considerations. By contrast, under a **decentralised** biosecurity system, national biosecurity objectives are implemented through decisions made by risk-creators, who face the full cost of their decisions and actions.

Asymmetric information: occurs when information is unevenly distributed amongst actors in the economy, particularly when one party to a transaction has more or superior information compared to another.

Catastrophe modelling: a technique used to quantify the potential financial impact of risk events that are infrequent, high-cost and for which there is limited historical data.

Complexities (market): the various factors and interactions that make buying and selling in markets more complicated, including policy, transaction, strategic, and timing complexities.

ELOP (Efficient Level of Protection): for biofouling, occurs where value created from transactions between all inbound vessels and the biosecurity authority (the market) is maximised considering all benefits and costs, including biosecurity costs.

Experimental economics: the testing and refining of incentive and information structures on human behaviour via economic experiments undertaken in a controlled environment (e.g., laboratory or field).

Game theory: allows the study of strategic behaviour between two or more agents when they have more than one strategy from which to choose and their choices affect the returns (i.e., payoffs) of another agent in the interaction.

Hidden action problem: also known as moral hazard, occurs when one party in a transaction or contract takes actions that are hidden from, or unobservable by, the other party.

Incentives: inducements for individuals to take actions that they would otherwise not consider. Incentive-compatible policies align the actions of self-interested individuals with a broader policy objective.

Incentive compatibility constraint: A policy is 'incentive-compatible' when each participant in their own interest makes decisions that are aligned with the objectives of the policy.

Market: places where buyers and sellers meet to trade goods and services. It is where the price and amount traded are determined; where the basic questions of what should be produced, how it should be produced and for whom, are solved.

Market design: a method for creating rules and processes to organise transactions to achieve a defined outcome.

Market failure: situations where transactions do not allocate goods and services efficiently. A range of factors can lead to market failure, including public goods, externalities, missing or weak property rights, lack of competition, and transaction complexities.

Missing market problems: occur when a market for a particular good or service doesn't exist, even though there are potential buyers and sellers to benefit from transactions. Causes include information and incentive problems, high transaction costs, lack of information, or externalities, all of which prevent the market from forming.

Moral hazard: see **hidden action problem.**

Principal-agent problems: occur where a task is delegated by a principal (who accrues the direct benefits of the task) to an agent (who bears the direct time and effort costs).

Public goods: types of goods where use by one person does not prevent access or reduce availability to other people. Those consuming public goods cannot be stopped from accessing them or failing to pay for them. Examples of public goods include ecosystem services, national security, or street lighting.

1. Executive Summary

The application of actuarial methods to price biosecurity risk fundamentally changes the way biosecurity could be managed in the economy. This report summarises research into biosecurity risk insurance completed under CEBRA Project 21C. It focuses on the structure of the market needed to manage biosecurity risks that arise from biofouling on inbound vessels. The findings are relevant to other biosecurity risks faced by Australia and have direct application to the design of an actuarial levy as a means of sustainably funding national biosecurity effort.

1.1 Key findings

1. The application of actuarial science in the biofouling domain could fundamentally change biosecurity risk management.

The emerging capability to price biosecurity risk through the application of actuarial science has been demonstrated in the biofouling domain. This capability fundamentally changes the way that biosecurity could be managed in the economy. Actuarial pricing can be implemented as a market for biosecurity risk insurance contracts or as an actuarial levy on the creators of biosecurity risk.

2. Actuarial pricing of biosecurity risk has efficiency, financial sustainability, timeliness and fairness advantages:

- Economic efficiency – actuarial pricing creates an incentive for risk-creators to change behaviour in ways that reduce Australia's exposure to biosecurity threats, and encourages them to seek cost-effective risk mitigation strategies.
- Financial sustainability – actuarially based biosecurity levies establish a pool of funds that is sufficient to cover expected losses arising from biosecurity incursions into the future.
- Timely response to incursions – the pool of funds created from a biosecurity risk insurance mechanism/actuarial levy would be available to immediately respond to exotic pest and disease incursions.
- Equity – actuarial pricing ensures that risk-creators fund biosecurity activities in proportion to their risk status.

3. Specific rules and processes must be designed to ensure efficiency and achievement of biosecurity objectives.

When applied to biosecurity risks arising from biofouling, specific rules and processes must be designed to ensure that a market for biofouling risk insurance/actuarial levy is efficient and achieves the biosecurity objectives intended. Key components are:

- Compulsory insurance/levy – legislation would be required to mandate the purchase of biofouling risk insurance/levy on all inbound vessels.
- Risk-rating inbound vessels – information needed to determine the risk status (provenance) of individual inbound vessels must be defined based on variables included in the actuarial pricing model (see Table 2 in the body of the report).

- Biofouling Management Plans – the biosecurity authority would require inbound vessels to reveal information needed to determine a vessel-specific risk rating through a structured process such as a Biofouling Management Plan (BMP).
- Adverse selection – risk-rating enables vessels to be matched to the correct vessel entry contract including the relevant actuarial levy.
- Incentive compatibility – incentive structures in vessel entry contracts will need to be designed so that the dominant strategy of the vessel operator is to truthfully reveal information (in the BMP) needed to determine the risk status of the vessel.
- WTO compliance – to ensure compliance with WTO conventions, incentive compatibility should be implemented (by the biosecurity authority) by adjusting audit/inspection probabilities rather than through taxes or subsidies on biosecurity interventions.
- Implementing the current biosecurity objective can be formally implemented through a market for biosecurity insurance/actuarial levy mechanism by imposing a fine on vessel operators (set at the marginal damage cost of false signalling) and then identifying the probability of audit/inspection needed to align the expected payoffs from alternative vessel entry pathways with the ordinal preferences (of the biosecurity authority) over vessel entry pathways.
- Efficient level of protection (ELOP) – an efficient level of protection can be implemented by allowing the market to choose the "best" vessel entry pathway.

1.2 Recommendations

In summary, recommendations are:

1. That actuarial pricing can be introduced to biosecurity risk management.

Actuarial pricing could be introduced to biosecurity risk management as either a formal market for biosecurity risk insurance or as an actuarial levy on risk-creators. These mechanisms have economic efficiency, efficacy and transparency advantages compared with a centralised approach to biosecurity management.

2. That investment be made into applying actuarial approaches.

Further investment will be needed to apply actuarial methods to all classes of biosecurity risk faced by Australia including from imported goods, plants and animals, and inbound passengers. Given the novelty of the actuarial approach, it will be crucially important to gain legal advice with respect to its status under WTO rules.

3. That investment be made in refining incentives more broadly in biosecurity.

Incentive structures that lead to truthful revelation of the risk status of creators of biosecurity risk must be designed as part of either a market for biosecurity risk insurance contracts or an actuarial levy mechanism. Further investment will be needed to refine these incentives across different classes of biosecurity risk.

4. Designed mechanisms and actuarial approaches should be tested in an economics laboratory.

Laboratory testing of a market for biofouling risk insurance/actuarial levy mechanism should be supported. Testing these mechanisms in the economics laboratory will produce estimates of the economic efficiency and efficacy advantages suggested from theory and increase familiarity with the mechanism.

2. Introduction

Non-indigenous marine species (NIMS) can cause economic, environmental, human health and amenity losses if transmitted to Australian ports on inbound vessels. Williams (1978) identified 20 species which have been introduced to Australian waters (see also Pollard and Hutchings, 1990) typically through biofouling of vessel hulls and ballast water discharge (Arndt et al., 2021). These and other biosecurity threats are currently managed by the biosecurity authority through a centralised approach, where activities including pre-border initiatives (e.g., surveillance), border controls (e.g., regulation and inspection of imported goods/inbound vessels), and post-border interventions (e.g., funded control and eradication programs) are imposed by biosecurity experts within a government agency. Management decisions are based largely on technical considerations.

The emerging capability to actuarially price biosecurity risk (Zhou et al., 2023; Appendix E) and its demonstrated application to biofouling (Zhou et al., 2025; Appendix F), fundamentally changes the way that biosecurity could be managed in the economy. This capability, if applied systematically, enables markets for biosecurity risk to be created in which prices act as an incentive for risk-creators to reduce Australia's exposure to biosecurity risk. It would also establish a sustainable pool of funds available to manage and respond to biosecurity threats as they occur.

Actuarial pricing of biosecurity risk can be implemented as either a *market for biosecurity risk insurance contracts* or as an *actuarial levy on risk-creators*. These mechanisms are used interchangeably in this report. The levy rate in the actuarial levy approach would be set at the same rate as the risk insurance premium in an insurance approach. They require the same supporting structures and can only be successfully implemented if incentive problems common to all risk markets can be resolved.

The broad objective of this report is to identify the economic architecture of a market for biosecurity risk insurance contracts/actuarial levy mechanism needed to implement actuarial pricing of biofouling risk. It applies market design concepts and incentive theory (as set out in Section 3 of the main report and Appendix A) to establish the rules and processes needed to organise the way inbound vessels would engage with the biosecurity authority to manage biosecurity risk through a decentralised approach to biosecurity. A brief summary of the foundation ideas, on which the report is based, is provided in the following section. Section 4 identifies the broad structure of existing markets for insurance contracts and Section 5 describes how these principles could be applied to implement specific biosecurity objectives. Section 6 identifies a number of complexities that will need to be considered if biosecurity risk insurance/actuarial levy mechanisms are to be implemented and Section 7 summarises key findings from the research completed so far.

3. Biofouling risk insurance

Exotic pests and diseases introduce risk into the Australian economy. In the marine context, each inbound vessel exposes Australia to possible economic, environmental, health and welfare losses if NIMS are inadvertently introduced. The role of Australia's biosecurity system is to reduce these risks and respond to unacceptable biosecurity risks as they arise. This response includes applying sanitary and phytosanitary protection measures to achieve ALOP and reduce biosecurity risks to a very low level, but not to zero. The department also applies other measures, such as biofouling risk management requirements, through administration of the *Biosecurity Act 2015* (Australian Government, 2015), to manage unacceptable biosecurity risks to a very low level, but for which ALOP does not apply *per se*. Notwithstanding this, this report uses the term ALOP to discuss all risks in a bid to simplify the comparison of Australia's current biosecurity objectives under the *Biosecurity Act 2015* and an alternative objective of efficient level of protection (ELOP).

Australia's biosecurity objective is currently implemented through a centralised planning approach involving regulation of risk-creators supported by interventions including border inspection, science, surveillance, and investments in preparedness and response capabilities where incursions are detected. In this approach to biosecurity risk management, decisions about the level of effort and allocation of resources are made by biosecurity experts based largely on technical considerations.

Stoneham et al. (2021, 2024) framed biosecurity as a missing market problem. Their analysis applied the Berliner (1982) assessment criteria to show that most risks arising from biosecurity threats are insurable. Furthermore, their research identified the cause of market failure as the difficulty, or even impossibility, of attributing pest or disease incursions to those responsible for creating these risks. In this context, markets for biosecurity risk insurance products have not emerged or been needed because individual vessel operators cannot be held accountable for the financial, economic, or human welfare losses they cause. These losses (a *negative biosecurity risk externality*) are currently borne by the Australian taxpayer. The appropriate policy response to this diagnosis of market failure was argued to include:

i. actuarial pricing of biosecurity risk;
ii. designing/creating a market for biosecurity risk insurance contracts to organise interactions between the biosecurity authority and inbound vessel operators; and
iii. compulsory participation by all risk-creators in a market for biosecurity risk insurance.

Zhou et. al. (2023; Appendix E) developed an actuarial methodology to price biosecurity risk based on: *expected annual losses* from biosecurity incursions; the *risk load* imposed to individual risk - creators; and the *expense load,* including administration, monitoring and response costs, incurred to manage biosecurity risk. The structure of the actuarial model for biosecurity risk insurance/actuarial levy was based on catastrophe modelling developed for risk events that are infrequent, high-cost and for which there is limited historical data (Grossi and Kunreuther, 2005; Mitchell-Wallace et al., 2017). This methodology was applied to biofouling by Zhou et al. (2025; Appendix F) using a mix of historical data (e.g., vessel arrivals at individual ports, movement history etc.) and synthetic data developed from a survey of scientists[1] to determine the relative likelihood of different incursion scenarios and the likelihood that NIMS introduced would require eradication or containment. Expert opinion was also used to build a model to estimate costs associated with a given incursion based on the probability of incursion scenarios. A statistical model was then developed to combine estimates of the frequency of NIMS incursions with incursion costs to compute estimates of the aggregate cost of biofouling risk insurance.

To determine the actuarial levy for individual vessels, vessel-specific risk ratings were identified from a range of scientific papers and expert opinion. Contributing risk factors include the age of anti-fouling coating, water temperature and salinity differentials between the destination and departure port, and the berthing duration of the vessel at the port. Actuarial levies defined at the individual voyage level were calculated by disaggregating the overall anticipated insurance costs according to the risk rating of each vessel.

Collectively, these methods were applied to create a statistical model from which the mean and standard deviation of the expected losses were derived. The actuarial levy was then calculated as the expected cost of containment/eradication plus biosecurity authority costs and a margin (related to the standard deviation of costs) to cover the risk. The same method would be applied to determine actuarial levies on inbound vessels.

Table D.1 reports indicative biofouling actuarial levy rates across the distribution of risk ratings. The six columns in Table D.1 represent six simulated vessels with distinct risk profiles. The 'Min' column corresponds to the vessel that paid the lowest premium among all simulated vessels, indicating the lowest biofouling risk. The other five columns represent an increasing biofouling risk, corresponding to the 25th percentile, median, mean, 75th percentile, and maximum premiums, respectively.

The premia in Table D.1 include biosecurity administration costs (estimated at $1,354[2] per arrival for commercial vessels) assuming a risk load of 3% of the standard deviation of annual loss[3]. An important feature of these premia is that a significant proportion (96%) reflects uncertainty arising from assumptions in the actuarial model with the remaining 4% reflecting expected losses arising from response costs (the risk component of premiums). As shown in Table D.1, premiums/levies increase with a higher risk load. For example, the median premium would increase from $2,618/vessel with a 3% risk load to $3023.5 with a 4% risk loading. The total premium paid by all vessels based on a 3% risk load is sufficient to cover response costs 90.1% of the time given that an incursion has occurred. To achieve a 95% chance of covering response costs, the median total premium per vessel would need to increase to $3,567.2 — the additional increase helps cover some scenarios with significant costs. The fact that most of the premium is allocated to risk load suggests our pricing is primarily structured to protect against rare but high-impact events, rather than merely covering the average cost of a biofouling incident.

[1] University of Melbourne Human Ethics ID: 2023-27400-42497-3

[2] Obtained from Biosecurity Cost Recovery Arrangement, Cost Recovery Implementation Statement 2023-2024 https://www.agriculture.gov.au/sites/default/files/documents/biosecurity-cost-recovery-implementation-statement-2023-24.pdf

[3] This assumption is subject to revision.

In determining the appropriate risk load, it is worth noting that in standard insurance practice companies could be required to hold capital sufficient to cover losses up to the 99.5th percentile[4] of risk. This means they must be prepared for very extreme scenarios, and the premiums they charge include a risk load that reflects the need to cover these potential losses. However, in a government-sponsored biofouling insurance scheme, the government is not bound by these strict capital requirements. Instead, the government can use its broader fiscal resources to cover losses if a worst-case scenario occurs. This flexibility means that the risk load — and hence the premium — can be tailored based on the government's overall risk appetite. However, if the risk load is set too high, the premium could discourage trade by making insurance prohibitively expensive. It is essential to balance fiscal prudence with keeping costs competitive.

Table D.1: Premiums for individual inbound vessels

Risk rating	Min (low-risk)	1st Quarter	Median	Mean	3rd Quarter	Max. (high-risk)
Premium (3% risk loading)	$313.2	$879.6	$1,264.7	$1,180.8	$1,436.2	$2,102.5
Premium (4% risk loading)	$ 416.5	$1,164.5	$1,669.5	$1,558.3	$1,893.5	$2,759.0
Administration costs	$1,354	$1,354	$1,354	$1,354	$1,354	$1,354
Total premium (3%)	$1,667.2	$2,233.6	$2,618.7	$2,534.8	$2,790.2	$3,456.5
Total premium 4%)	$1,770.5	$2,518.5	$3,023.5	$2,912.3	$3,247.5	$4,113.0

^Note that ‘Premium’ includes expected costs and risk loading, while ‘Total premium’ also includes Administration costs

Given the assumption that an incursion is expected on average every five years across Australia, approximately 80% of years would be event-free. When considering only the vessel arrivals at the six ports as assumed by the model, about 95% of years would be event-free. Combined, the event-free years and the years where incursions occur but the premium is sufficient to cover response costs account for approximately 99.5% of all years.

In years without any events, the premium can be saved as a reserve. In the insurance industry, such reserves are typically invested. This buffer can then be used in years when a major event causes costs that exceed the annual premium. Note that the response cost for those years with a major event can be very large. Essentially, we need to save to ensure that, when severe events occur, there is sufficient funding available to cover the excess costs.

[4] This approach is common in the financial industry; for example, under the Solvency II framework in Europe, insurers must maintain such capital buffers. In Australia, the Australian Prudential Regulation Authority (APRA) enforces similar capital requirements for insurers.

4. Structure of a market for a biofouling actuarial levy mechanism

Monetising biosecurity risk through actuarial pricing, opens up the prospect of transitioning management of this important class of risk from a centrally planned approach (the current biosecurity system) to a decentralised approach. In a decentralised biosecurity system, national biosecurity objectives would be implemented through decisions made by risk-creators who face the financial consequences of their actions including the expected cost of biosecurity risk (i.e., biosecurity risk insurance premium/actuarial levy) imposed on the host country. This approach to biosecurity management could be implemented as either a *market for biosecurity risk insurance contracts* or as an *actuarial levy mechanism* in which participation would be compulsory. Both rely on the application of actuarial methods to determine insurance premiums/levy rates, compulsory participation, and resolution of specific information and incentive problems that would otherwise impede the efficiency, efficacy and financial sustainability of the proposed mechanism. The levy rate, in the actuarial levy approach, would be set at the same rate as the risk insurance premium in an insurance approach.

Although biosecurity displays specific complexities, the broad economic structure of a market for biosecurity risk insurance contracts/actuarial levy mechanism can be observed from insurance markets that exist in other domains of the economy. These markets are defined by rules and processes that organise transactions between two types of actors the *principal* (the insurance business) and *agents* (actors that create risk). Value is created from these transactions because the principal (a large, diversified organisation) has a lower cost of risk bearing (due to risk pooling) than the agent (a small, often specialised business or individual). In the biosecurity context, actuarially priced biosecurity risk insurance premia/actuarial levies redistribute risk (referred to as *risk transfer* in actuarial science) from individual vessel operators (agents that create risk) to the Australian Government (the principal represented by the biosecurity authority) through a contract. Transactions that transfer risk in this way create value because the biosecurity authority pools risk across all biosecurity risks thereby reducing the cost of risk bearing compared with individual vessel operators. Although the current biosecurity system also redistributes biosecurity risk from risk-creators to the Australian Government (realising the benefit of risk pooling); it does not create incentives for risk-creators to reduce national risk exposure (by monetising biosecurity risk) and does not require risk-creators to fund the biosecurity system. The extent to which a biosecurity risk insurance market/actuarial levy mechanism is more efficient, effective and financially sustainable than the current (centralised) approach depends on whether problems of *moral hazard* and *adverse selection*, common to all insurance markets, can be addressed. These are discussed in the following sections.

4.1 Moral hazard

Moral hazard occurs when the behaviour of the insured party changes because they take out insurance. For example, individuals who take out motor vehicle insurance no longer bear the cost of accidents and may change their driving behaviour in ways that increase the insurer's loss exposure (e.g., less effort in avoiding theft; greater vehicle use). These changes in behaviour are hidden from the insurer (referred to as the *hidden action* problem) but influence the outcomes (*efficacy*) of insurance schemes. Stoneham et al. (2021) argued that while markets for biosecurity risk insurance display opportunities for moral hazard (i.e., deliberate release of exotic pests in Australia), there is no incentive for risk-creators to engage in such activities. In the biofouling context, for example, there is no financial advantage for vessel operators to deliberately introduce NIMS into Australia such that moral hazard is not a primary design problem in markets for biosecurity risk insurance/actuarial levy mechanisms. In the biofouling context, there is no benefit to be gained from changing behaviour once the vessel has been allocated to an insurance contract. Such vessels would be in transit to a destination port after which there would no financial gain (incentive) that might lead vessel operators to change behaviour in ways that would impact on national biosecurity risk exposure. The main market design problem relevant to biosecurity risk insurance is with respect to the rules and processes needed to allocate insurance contracts efficiently (adverse selection). This is the aspect of the market for biosecurity risk insurance where vessel operators can behave strategically to gain an advantage e.g., through false signalling.

4.2 Adverse selection

In an insurance context[5], adverse selection refers to the problem of allocating agents with different risk profiles, to contracts in which insurance premiums reflect the agent's risk rating. This problem arises because individuals/organisations wishing to purchase insurance contracts hold information needed to determine their risk rating (Laffont and Martimort, 2002). In a market for biosecurity risk insurance, there is scope for vessel operators to behave strategically for financial advantage before biosecurity risk insurance contracts are allocated. The adverse selection problem in this context is amplified because it is costly to inspect all vessels to determine their biofouling risk rating, before they enter the destination port. In this instance, risk rating, and insurance premiums, will be based on information revealed by vessel operators but not known by the insurer (i.e., asymmetric information). In insurance markets, specific rules and processes have been developed to mitigate the adverse selection problem. These include: creating an *information space* which defines specific information that agents must reveal to the insurer; developing a *risk rating process* as the basis of allocating agents to the "best" contract (including risk premium); and establishing a *menu of contracts* for different *types* of agents. The following sections discuss how these processes might be engineered into a market for biosecurity risk insurance/actuarial levy mechanism in the biofouling domain.

4.2.1 BIOFOULING INFORMATION SPACE AND RISK RATING PROCESS

The biosecurity risk posed by inbound vessels varies according to a range of vessel design, operation, provenance and environmental factors. In a decentralised biosecurity system, the biosecurity authority must precisely specify information (*variables*) needed to determine the risk rating of each inbound vessel and measurement protocols (*metrics*). This is referred to as the *information space*. In a market for biosecurity risk insurance/actuarial levy mechanism, the information space is defined by variables and metrics specified in the actuarial pricing model developed by Zhou et al. (2023). These are identified in Table D.2.

[5] Adverse selection is a problem that needs to be resolved in all markets.

Table D.2: Biosecurity risk rating proforma for inbound vessels

Vessel information	Explanation
1. Type of vessel	Class of vessel entering Australian port
2. Type of port	Degree of enclosedness
3. Temperature	Absolute difference in mean temperature between origin and destination port
4. Salinity	Absolute difference in mean water salinity between origin and destination port
5. Duration	Length of stay in port
6. AFC vintage	Age of anti-fouling coating (AFC)
7. Vessel speed	Average speed of vessel — related to vessel type

Existing information gathering methods, such as Biofouling Management Plans (BMPs) [6] could be adapted to establish the information space needed in a market for biofouling risk insurance contracts/actuarial levy mechanism. These would need to be standardised across the shipping sector to include information about: the type of vessel (variable 1 in Table D.2), voyage history log (to determine temperature and salinity differences in variables 3, 4 and 6), anticipated length of stay (5), anti-fouling history, actions to mitigate risk (e.g., vessel cleaning actions) and status (6). This information could also include certifications needed to assist the biosecurity authority with verification and electronic lodgement with the biosecurity authority while the vessel is sailing. Risk rating and premium/actuarial levy calculation based on methodologies developed in the actuarial model could be completed before vessels enter Australian waters as part of the information architecture of the market.

4.2.2 ALLOCATING INBOUND VESSELS TO INSURANCE CONTRACTS/ACTUARIAL LEVY RATES

Figure D.1 illustrates two stages of a biosecurity system implemented through a market for biosecurity risk insurance. In the first stage, (s=1.1) the biosecurity authority designs, implements rules and processes that define how vessel operators engage in the biosecurity system. Vessel operators, considering the financial benefits derived from shipping cargo and the costs incurred from biosecurity related activities, choose the level and type of investment in biosecurity mitigation effort (s=1.2) including investments in vessel design and anti-fouling coating (AFC) and a vessel entry strategy (discussed below). These decisions are made before the vessel sets sail for the destination port.

Stage 2 in Figure D.1 describes the rules and processes that apply once the vessel commences its voyage and is required to engage with the biosecurity system in the destination country. The key task of this stage in a biosecurity risk insurance approach is to allocate vessels to the relevant insurance contract including the risk-based insurance premium they will be required to pay — the adverse selection problem. Three components of this stage are noted in Figure D.1. The first (s=2.1) requires vessel operators reveal information (defined in Table D.2) needed to determine the vessel's biosecurity risk rating. In this stage, profit-motivated vessel operators could seek to minimise costs by falsely revealing this information so that are allocated to a contract defined by a lower risk and a low biosecurity risk insurance premium (see Table D.1). The opportunity for false signalling of biosecurity effort arises because it is

[6] BMPs are vessel specific documents that report biofouling management activities.

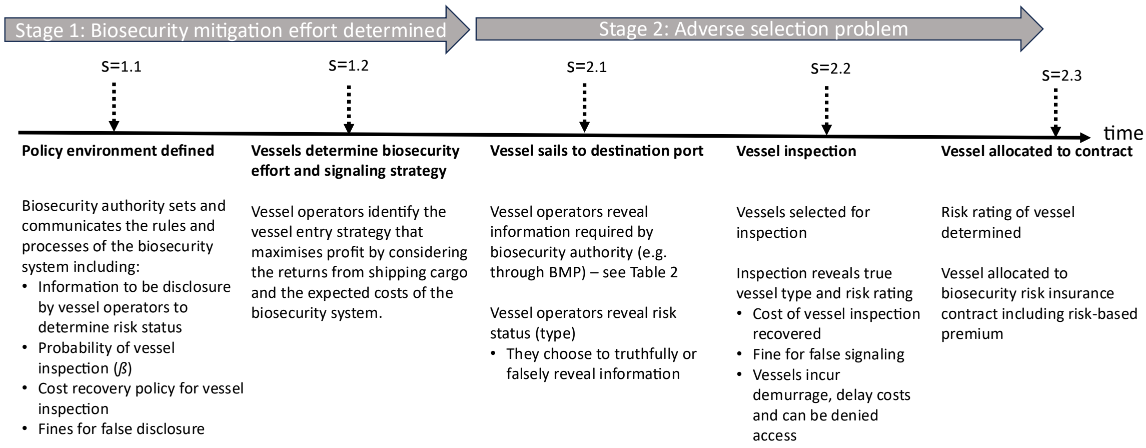

Figure D.1. Stages of a biosecurity risk insurance approach to biosecurity

not feasible for the biosecurity authority to inspect all inbound vessels. To counter this problem, a vessel inspection regime (s=2.2) is introduced including fines for false declarations/signalling. Based on the information revealed by vessel operators and the outcome of vessel inspection (where they apply), vessels are assigned a risk rating (based on the actuarial model) and allocated to the relevant biosecurity risk insurance contract including the relevant risk-based insurance premium (s=2.3).

Figure D.2 provides a more detailed illustration of the interaction between vessel operators and the biosecurity authority in Stage 2 and the origin of the adverse selection problem. It frames this aspect of the biosecurity system as a 'game' in which there are two actors: the biosecurity authority (*principal*) and vessel operators (*agents*). The task for the biosecurity authority is to identify the specific rules and processes needed to align the actions of profit-motivated vessel operators with a stated national biosecurity objective. Minimising biosecurity costs (broadly economic efficiency) and achieving financial sustainability are identified as additional components of the biosecurity objective where a biosecurity risk insurance mechanism is used to implement the biosecurity system.

Figure D.2 identifies six interventions (activities; P.1…6) by the biosecurity authority that will be needed to implement a market for biosecurity risk insurance contracts. These interventions establish the information, incentive and participation architecture needed to allocate each inbound vessel to the biosecurity risk insurance contract/premium that reflects the vessel's risk rating. In response to the financial advantage of false signalling by vessel operators and the high cost of vessel inspection, a *vessel inspection regime* (market design task P.3 in Figure D.2) is included in the market structure. In this component of the market, the biosecurity authority identifies the fraction of inbound vessels (*ß*) that will be required to complete vessel inspection. A methodology for determining *ß* is discussed later in the report.

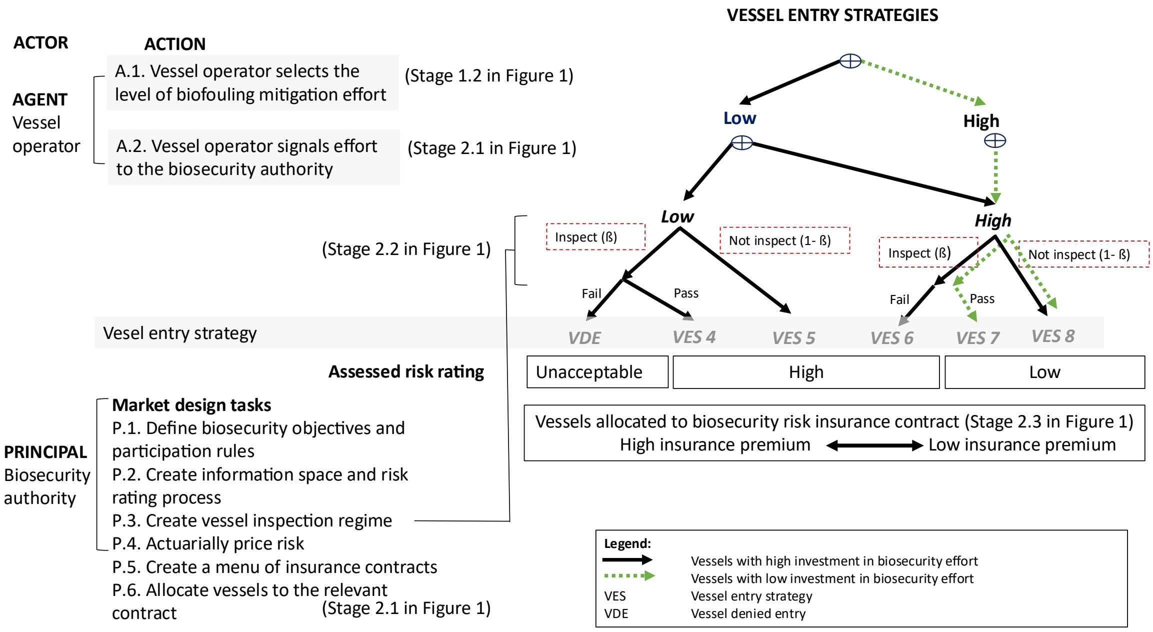

Figure D.2. Game theoretic framing of the adverse selection problem

Once the rules and processes that define the biosecurity system are established by the biosecurity authority, vessel operators make two interrelated strategic decisions. They determine both the level of investment mitigation effort (A.1 in Figure D.2) and select their signalling strategy (A.2). For illustrative purposes, Figure D.2 depicts only two types of vessel operators — those that invest high-effort in biosecurity mitigation effort (High) and those that invest low-effort (Low). Clearly, the decision to invest high- or low-biofouling mitigation effort interacts with the signalling strategy selected by vessel operators (A.2 in Figure D.2). For example, a profit motivated vessel operator will select low-effort if there is a low probability of being selected for vessel inspection and/or the financial consequences of false signalling are low relative to the benefits.

Interactions between the strategic decisions of vessel operators (A.1 and A.2) and rules and processes of the biosecurity system (P.1…P6) create a range of *vessel entry strategies* (VES) available to vessel operators. For example, VES 6 represents a vessel operator whose pathway through the biosecurity system is defined by: low-biosecurity mitigation effort (denoting high biosecurity risk); a false "High-effort" signal to the biosecurity authority; selection for vessel inspection; and a failed inspection result. This vessel would be assigned a "High" risk rating by the biosecurity authority (assuming vessel inspection is infallible) and assigned to a contract specifying a high biosecurity risk insurance premium. If this vessel were not selected for inspection (probability 1- β), it would be defined by VES 8 resulting in a "Low" biosecurity risk rating even though its true risk rating is "High" and assigned to a contract with a low insurance premium — resulting in an adverse selection problem. Rational vessel operators, motivated by self-interest, will compare the expected financial consequences of all possible VES and then select the one that maximises profit. The VES with the highest expected financial payoff to the vessel operator is referred to as the *dominant strategy*.

The following sections identify the rules and processes (market structure) needed to resolve the adverse selection problem (economic efficiency), and create a financially sustainable (capable of funding expected losses) and efficacious (implements national biosecurity objectives) biosecurity system through a market for biosecurity risk insurance.

4.2.3 OBJECTIVES OF A MARKET FOR BIOSECURITY RISK INSURANCE

The objective of most markets for insurance is to maximise value created from transactions and to achieve financial sustainability. Economic efficiency is achieved in these markets where no change in transaction parameters including buyer and seller pairings, prices and volumes transacted can be made to improve value created — the adverse selection problem. Financial sustainability is achieved where premiums establish an insurance pool capable of covering loss exposure — actuarial pricing. The objective of biosecurity systems operating in most countries is, however, defined in terms of achieving a target exposure to biosecurity risk referred to as an appropriate level of protection (ALOP). In Australia, for example, ALOP[7] is defined in legislation as a "*very low level*" of biosecurity risk exposure (Australian Government, 2015). Australia's national biosecurity agency also applies other measures, such as biofouling risk management requirements, through administration of the *Biosecurity Act 2015,* to *manage certain unacceptable biosecurity* risks for which ALOP does not apply *per se*. The ALOP objective is sanctioned by the World Trade Organisation (WTO) provided measures do not constitute unjustified non-tariff barriers to trade and, where justified, must be the least trade-restrictive measures necessary to achieve a country's ALOP, consistent with WTO obligations (Fraser et al., 2019; Bland et al., 2024).

Where implemented through a market for biosecurity risk insurance, the objective (the given in designing the market) can be defined in terms of:

i) *National biosecurity objectives* – implementing a stated national biosecurity risk exposure target defined by ALOP;

ii) *Economic efficiency* – minimising the adverse selection under the ALOP target; and

iii) *Financial sustainability* – creating biosecurity insurance pool capable of covering the cost of administering the biosecurity scheme and funding the costs of responding to exotic pest and disease incursion.

Economic efficiency and financial sustainability can be engineered into a market for biosecurity risk insurance through rules and processes that mitigate adverse selection and introduce actuarial/risk-based premiums. In most countries, however, the ALOP objective would need to be formalised for it to be implemented through a decentralised biosecurity system. In the biosecurity system illustrated in Figure D.2, an ALOP of "very low level" of biosecurity risk exposure could only be achieved by inbound vessels that invest high-biofouling mitigation effort. These are identified as VES 8 and VES 7 in Figure 2 which are assigned a low-risk rating. Vessels with a high risk-rating (VES 4…6) or unacceptable risk-rating (VDE; Vessel Denied Entry) would not be permitted entry under this definition of ALOP.

[7] ALOP in Australia is defined "as a high level of sanitary and phytosanitary protection aimed at reducing biosecurity risks to a very low level, but not to zero".

Alternatively, monetising biosecurity risk opens-up the prospect of defining the objective of a biosecurity system in terms of maximising value created from transactions — as is the case in most markets for insurance. We refer to this as an *efficient level of protection* (ELOP). Under this objective, vessel operators, considering all relevant costs and benefits of alternative vessel entry strategies, choose the level of biofouling mitigation effort that maximises value created. The implications of both ALOP and ELOP are explored later in the report.

4.2.4 PARTICIPATION RULES

Unlike most markets where participation is voluntary and motivated by self-interest, the attribution problem (noted above as the participation complexity) denotes that all inbound vessels would be required to purchase biosecurity risk insurance. Legislation would be needed to enforce this participation requirement. Revenue from insurance premiums would contribute to a biosecurity risk insurance pool which would be drawn on by the biosecurity authority to respond to incursion events, fund biosecurity administration, monitoring and surveillance costs.

4.2.5 INFORMATION STRUCTURE AND RISK RATING PROCESS

'Information structure' refers to variables, metrics and certifications that define attributes of an item or service being transacted. More formally, the information structure of a market is a component of the *message space* that enables buyers and sellers to communicate so that transactions can be executed (see Macho-Stadler and Pérez-Castrillo, 2001; Hurwicz and Reiter, 2006). In insurance markets it is defined by variables that contribute to risk exposure in the actuarial model — identified in Table D.2. Some of this information, including type of port, temperature and salinity differences between itinerate ports, is readily available to the biosecurity authority. Other information, including the type of vessel, vessel movements, sailing speed, investment in biosecurity mitigation effort (AFC investment and age) is private information that must be revealed by vessel operators to the biosecurity authority so that a *risk rating* can be determined for each inbound vessel. The information space in a market for biosecurity risk insurance must precisely identify the variables, metrics (also defined by the actuarial model), measurement protocols, certifications and lodgement protocols all of which will need to be standardised into vessel entry protocols in a market for biosecurity risk insurance. Stoneham et. al. (2024) suggests BMPs could be adapted for this purpose.

4.2.6 VESSEL INSPECTION REGIME

Engineering truthful revelation of information into markets involving private information is an important market design problem. In the biofouling context, the high costs of inspection, demurrage and delay effectively exclude inspection of all inbound vessels as the means of information revelation. This problem arises in many other markets, where it is often framed as an "*inspection game*" — a framework used to determine the probability of inspection effort (sampling fraction and type of inspection) and the financial penalties for false declarations, so that truthful revelation of information becomes the dominant strategy for market participants. The decision environment faced by actors in this type of game can be represented as a decision tree in which all possible decision points are identified along with the expected payoffs (see Avenhaus et. al., 2002; Surkov et al. 2008, Rossiter and Hester, 2017; Stoneham et al., 2024).

Complexities arising from the structure of the market (e.g., vertical integration), dynamic interaction between actors (e.g., adaptive inspection rules and reputation), and other refinements can be introduced to reflect more complex decision environments.

Framing the current problem as an inspection game reveals three *control variables* that the biosecurity authority can implement to mitigate false signalling. These are:

i) Cost recovery policy for inspected vessels,

ii) Monetary value of fines where vessel operators are discovered to falsely signal vessel effort to the biosecurity authority, and

iii) Probability of inspection (β).

The task for the biosecurity authority is to engineer these control variables to establish an incentive structure in which the dominant strategy of vessel operators is to truthfully signal/reveal information needed to determine the risk rating of their vessels. This outcome can be achieved with different settings of the control variables. For example, introducing a higher monetary fine for false signalling (ii), will require a lower probability of vessel inspection (iii) to motivate truthful revelation of information. Two of the three control variables (i and ii above) can be set exogenously through the application of economic principles (embedded in international trade obligations) with the probability of inspection (iii) to be determined endogenously by the biosecurity agency.

Cost recovery

Agreements under the WTO oblige member countries to reduce or eliminate tariffs, quotas and other restrictions that distort international trade. Under these agreements, biosecurity interventions are monitored to avoid them being used as non-tariff barriers to trade. To comply with these obligations, vessel inspection costs and the monetary value of fines (taxes) should be set at levels that promote economic efficiency. This suggests that vessel operators should bear the full cost of vessel inspection as part of their vessel entry strategy.

Fine for false signalling

Economic efficiency principles can also be applied to determine the monetary value of fines for false signalling. False signalling by one vessel operator effectively imposes vessel inspection costs on other vessel operators (referred to as a negative externality) who truthfully signal information to the biosecurity authority. The negative externality problem has been extensively studied in environmental applications where harmful emissions from one factory impose costs (a negative externality) on others in the form of human health and environmental costs. For these problems, a tax on the source of emissions set at the marginal cost of damage caused to others (referred to as a *Pigouvian tax*; Pigou, 1920) has been identified as the efficient response. Applying this principle in the current context means the optimal tax for false signalling of information should be set at the marginal cost that false signalling behaviour imposes on other vessel operators. This suggests that the monetary value of the fine for false signalling should be set at the expected cost of vessel inspection, demurrage and other delay costs that occur when vessels are selected for inspection.

Probability of inspection

Following the application of economic efficiency principles to cost recovery and false signalling, the task for the biosecurity authority is to identify the probability of vessel inspection (β) needed to align the actions of vessel operators with the stated biosecurity objective. Markets/mechanism that achieve this alignment are referred to as *incentive-compatible*. A market designed in this way will lead vessel operators to invest in the level of biosecurity mitigation effort (action A.1 in Figure D.2) that aligns with the stated national biosecurity objective. The following sections demonstrate how the probability of vessel inspection would be calculated to implement an incentive-compatible market for biosecurity risk insurance where either ALOP or ELOP are defined as the objective.

5. Implementing alternative biosecurity objectives through a market for biosecurity risk insurance

In a decentralised approach to biosecurity, vessel operators make decisions about the level of investment in biofouling mitigation effort by considering all costs and benefits of alternative vessel entry strategies. The role of the biosecurity authority is to design the market, specifically to formalise the objective(s), design participation rules and establish the incentive structure needed to create an information efficient, incentive-compatible decision environment. To demonstrate this approach an indicative payoff matrix (Table G.1, Appendix G) has been created to broadly reflect the financial costs and benefits that would apply to each of the vessel entry strategies illustrated in Figure D.2. Key features of the payoff matrix include:

- Biofouling mitigation investments such as the application of antifouling coating of vessel hulls, can be costly. When spread over the vessel operations, these costs are a relatively small component of costs in the payoff matrix.
- Biosecurity risk insurance premiums are set at actuarial rates shown in Table D.1.
- The cost of biofouling mitigation effort and risk insurance premiums are not conditioned by the probability of inspection.
- Demurrage and delay (rescheduling) costs are known by vessel operators (private information) but are considered high relative to other elements of the payoff matrix.
- The monetary value of vessel inspection is based on cost recovery.
- The monetary value of the fine for false signalling set at marginal damage cost — the sum of vessel inspection plus delay costs.
- Vessel inspection costs, demurrage and delay/rescheduling costs are only incurred if vessels are selected for vessel inspection.

Some elements of the payoff matrix, such as the financial cost of delays to vessel scheduling, are private information known only by vessel operators. Other elements, such as biosecurity risk insurance premia and vessel inspection costs are set by the biosecurity authority. Whilst elements of the payoff matrix will vary between vessel operators, the incentive structure defined in Table G.1 has been created to broadly reflect the relative importance of costs faced by commercial vessel operators. Appendix G provides more detail on elements of the payoff matrix.

A rational vessel operator will make decisions about the level of effort they invest in biosecurity mitigation (Action A.1 in Figure D.2) and their signalling strategy (Action A.2 in Figure D.2) by considering the expected payoff for all VES. In this calculation, the vessel operator will consider monetary values represented in the payoff matrix and the probability of incurring each cost item. The task for the biosecurity authority is to create an incentive structure such that the dominant strategy of vessel operators is to choose the VES that implements the stated biosecurity objective. With vessel inspection set at full cost recovery, fines for false signalling set as a Pigouvian tax, and other costs broadly indicative of the shipping sector, we compute the probability of inspection (β) needed achieve this outcome for ALOP (Section 5.1) and ELOP (Section 5.2). For illustrative purposes, this analysis is restricted to VES relevant to "Low"-effort vessels.

5.1 Implementing an appropriate level of protection

Figure D.3 reports the expected payoff from vessels with low-biosecurity effort (VES 4,5,6) and high-biosecurity effort (VES 7,8) over a range of probabilities of inspection. Expected payoffs are determined by calculating the expected payoff from sequences of decisions that define each VES. To identify the most advantageous VES, a vessel operator will consider: the cost of achieving different risk ratings (Unacceptable, Low, High), the biosecurity risk insurance premium that would apply to each risk rating; and the expected (negative) payoff for truthful/false signalling given the probability of a vessel being selected for inspection (β) and the financial penalties (the full cost of vessel inspection, fines for false signalling, demurrage and scheduling delay costs). Based on the example payoff matrix defined in Appendix G, Figure D.3 shows that a probability of inspection of β = 0.065 (one in every 15 vessels inspected) would be required to create an incentive compatible market for biosecurity risk insurance. At this probability of inspection, the expected payoff from the additional investment in vessel design and AFC treatments needed to achieve a "Low"-biosecurity risk rating (ALOP) will exceed the expected payoff from all other VES. At this probability of inspection, the biosecurity system is *incentive-compatible.* Based on the payoff matrix in Table G.1, the expected cost per vessel of implementing ALOP through an insurance mechanism in which one in 15 vessels are inspected would be $19,616.

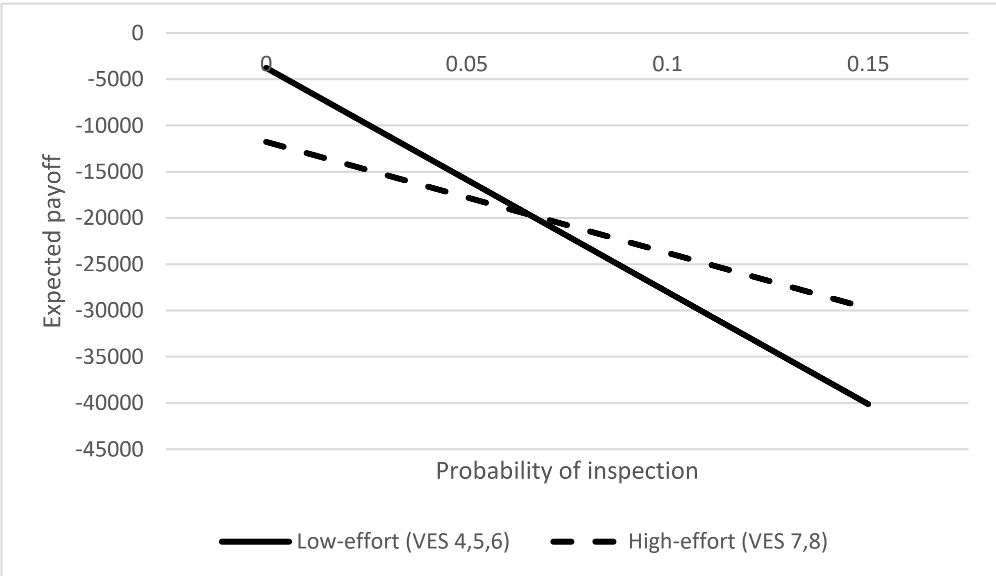

Figure D.3: Probability of vessel inspection needed to achieve ALOP

5.2 Implementing an efficient level of biosecurity protection

An efficient level of protection (ELOP) occurs when transactions in biosecurity risk insurance contracts maximises value created across all transactions in the market. In this biosecurity system, ELOP will be determined by the decisions of vessel operators (not by the biosecurity authority) in light of all relevant costs and benefits. Because there is no predetermined biosecurity risk target/objective, ELOP will be achieved where the probability of vessel inspection creates an incentive structure in which the dominant strategy of vessel operators is to truthfully reveal (signal) information needed to determine the vessel's risk rating. Figure D.4 reports the expected payoff to vessel operators from truthful and false signalling strategies. This figure shows that the probability of vessel inspection would need to be *ß* = 0.0191 (1 vessel in 52) before truthful signalling of information (needed to implement ELOP), becomes the dominant strategy. The expected cost per vessel of implementing ELOP through an insurance mechanism would be $8,411.

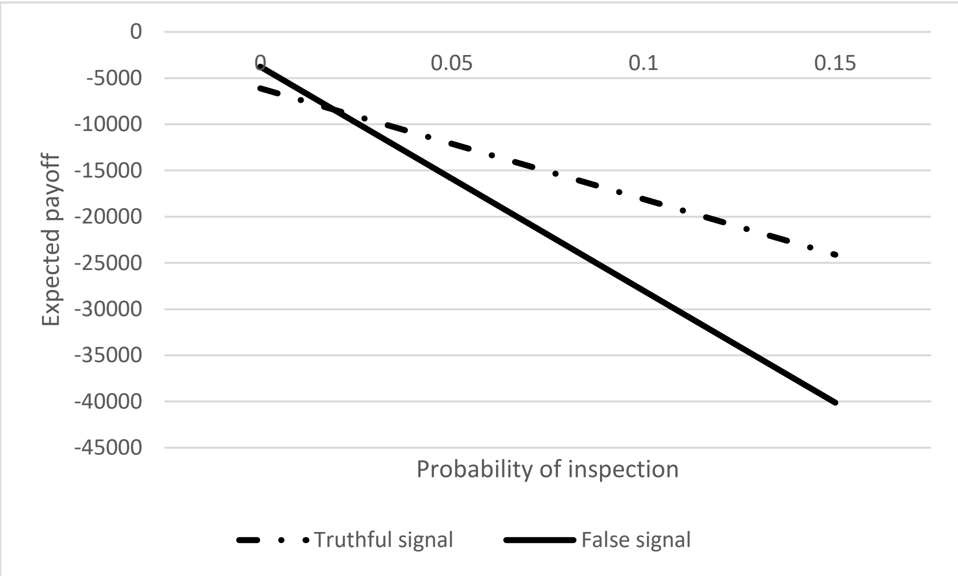

Figure D.4: Probability of vessel inspection needed to achieve ELOP

5.3 Economic efficiency implications

While a biofouling case study was used to demonstrate the efficiency gains of a decentralised approach to biosecurity, the information and incentive advantages of a decentralised approach to biosecurity can be expected to improve economic efficiency in this domain of the economy more broadly. In the absence of empirical evidence, some indication of the scale of these gains can be estimated by comparing the expected payoff/cost of implementing ALOP with the expected payoff/costs of implementing ELOP. In this comparison ALOP is a technical target typically adopted in centrally planned biosecurity systems whereas the ELOP is an economic objective only possible under a decentralised approach to biosecurity. Table D.4 shows that the expected costs to vessel operators of complying with the biosecurity system fall from $19,616/vessel, where a centrally determined objective of ALOP is adopted, to $8,411/vessel where the market determines the efficient level of protection — a 57% improvement in economic efficiency.

Much of the economic efficiency gain can be attributed to information advantages of a decentralised approach to biosecurity. In a market for biosecurity risk insurance, the information structure is specifically designed to generate and assemble all relevant information into the *message space* in which decisions are made. This includes information about the: price of biosecurity risk, full cost of vessel inspection, efficient cost of signalling externalities, and private information about the costs of demurrage and scheduling costs arising from biosecurity interventions incurred from delays. Consideration of these costs enables vessel operators to determine their efficient level of biosecurity mitigation investment. Many of these costs are not known by the biosecurity authority and are not taken into account when establishing centrally planned biosecurity objectives. Reductions in the probability of inspection from one in 15 to one in 52 inbound vessels, represent the economic efficiency dividend from the decentralised approach to biosecurity.

These results are subject to a range of assumptions, one of which is that risk is priced efficiently. Sensitivity to this assumption is reported in Table D.4, where it is shown that the economic efficiency gain from ELOP falls to 42% if the insurance premium is doubled. This analysis is relevant given that biosecurity risk insurance premiums reported by Zhou et al. (2025) exclude that component of biosecurity risk considered to be non-insurable according to the Berliner (1982) criteria.

Table D.4: Expected cost per Low-effort vessel (4% risk loading)

Biosecurity objective:	$\beta^{\#}$	**Expected payoff**	**Expected payoff (premium x 2)**	**Change in expected cost (%)**
ALOP	0.065	-$19,616	-$21,239	$1,623 (8%)
ELOP	0.019	-$8,411	-$14,736	$6,324 (75%)
Cost reduction ($)		$11,206 (57%)	$6,503 (31%)	-$4,703 (-42%)

6. Discussion

The economic structure of a market for biosecurity risk insurance contracts/actuarial levy mechanism identified in this report depends on the implications of several assumptions. These are discussed below.

6.1 Vessel operator reputation

The biosecurity system presented in this report has been framed as a "one-shot" game in which there is no provision for retaining information about the vessels'/vessel operators' previous interaction with the biosecurity system. There is clearly scope to consider how a market for biosecurity risk insurance contracts/actuarial levy mechanism might retain and utilise reputation to improve the economic efficiency and efficacy of the biosecurity system. For example, vessel operators who establish a reputation for truthful signalling of biofouling effort could be rewarded through financial and or vessel inspection concessions applying to future interactions. A *repeated game* framing of the biosecurity system in which the risk rating process is based on current and prior information (see Rossiter and Hester, 2017) will be needed to identify the control variables needed. If well-designed, a biosecurity system that includes reputational incentives could create dynamic incentives that can be expected to further reduce the expected cost for reputable vessel operators and increase expected costs for non-compliant operators.

6.2 Vessel type-space

The objective of this report has been to demonstrate how to design a biosecurity risk insurance mechanism. For simplicity, we have restricted payoff matrix to VES available to low-effort vessel operators. Expanding the number of types in the economic model of biosecurity will create a more complex transaction environment characterised by a larger number of branches, vessel entry pathways and contracts in the menu. Expanding the type-space to reflect heterogeneity in vessel operators will be needed to fine-tune economic design suggesting that an investment in computer-based models of the biosecurity system will be needed.

6.3 Inspection regime

The inspection game assumed in the biosecurity system described in this report is highly simplistic. It assumes all inbound vessels face the same probability of inspection (β), and only one form of vessel inspection is employed. At least three types of inspection were identified in Section 4.2.2:

i) auditing BMPs while vessels sail to Australia (a low-cost inspection regime);
ii) vessel inspection to determine biofouling effort (a moderate-cost option); and
iii) vessel inspection to determine NIMS status (a high-cost option).

A vessel inspection regime incorporating combinations of these options, including sequential inspection pathways and Bayesian probabilities will create a more effective inspection process and a more complex market design environment. For example, a vessel inspection regime could be constructed in which there would be a higher probability of inspection for low-cost/minimal delaying forms of inspection (e.g., BMP audit) with subsequent, more costly, vessel inspection interventions (ii and iii) triggered by audit results and vessel reputation. Whilst the principles developed for a simple inspection regime apply more generally, computer-based Bayesian probability models will be needed to determine the optimal inspection regime.

6.4 Efficient pricing of risk

One important assumption underpinning economic efficiency in all domains of the economy is that of efficient prices. In the biosecurity domain, actuarial methods lead to efficient pricing of risk but it is important to recognise that premiums/actuarial levy rates developed by Zhou et al. (2023, Appendix E; and 2025, Appendix F), cap loss exposure to response costs and biosecurity system costs. The premiums reported in Table D.1 do not include losses, such as ongoing environmental/human health or amenity losses, that would arise if a NIMS became endemic and spread across Australian ports. Whilst these losses are arguably less likely than could be expected from biosecurity threats to terrestrial animals and plants (e.g., foot and mouth disease), there is some residual un-priced risk not reflected in the actuarial model. These risks were excluded from the actuarial model because they were assessed by Stoneham et al. (2021) to be systematic risks that are uninsurable according to the Berliner (1982) risk assessment criteria. Nevertheless, systematic biosecurity risk carries some level of loss exposure that needs to be priced or managed in some way. Under the current biosecurity system, both systematic and unsystematic biosecurity risk is carried by sectors of the economy impacted by biosecurity risk and the Australian government which also informally underwrite these risks.

From a market design perspective, exclusion of systematic risk in biosecurity risk insurance premia/actuarial levy rates will lead to some level of underinvestment in biosecurity mitigation effort. Based on the example biosecurity system developed for this report, the impact of this problem may be relatively minor. Figure D.5 illustrates the impact of increasing premium rates (to include currently un-priced systematic risk) on the expected cost to vessel operators under the ALOP biosecurity objective. From this figure, it can be seen that even large increases in the biosecurity risk insurance premiums/actuarial levy rates result in small percentage changes in the expected biosecurity-related costs of vessel operators. For example, three times increase in the biosecurity risk insurance premium reduces expected costs by only 7%. This relationship occurs because premiums/actuarial levy rates are small relative to other costs in the example payoff matrix. Based on the example payoff matrix in Appendix G, a three times increase in

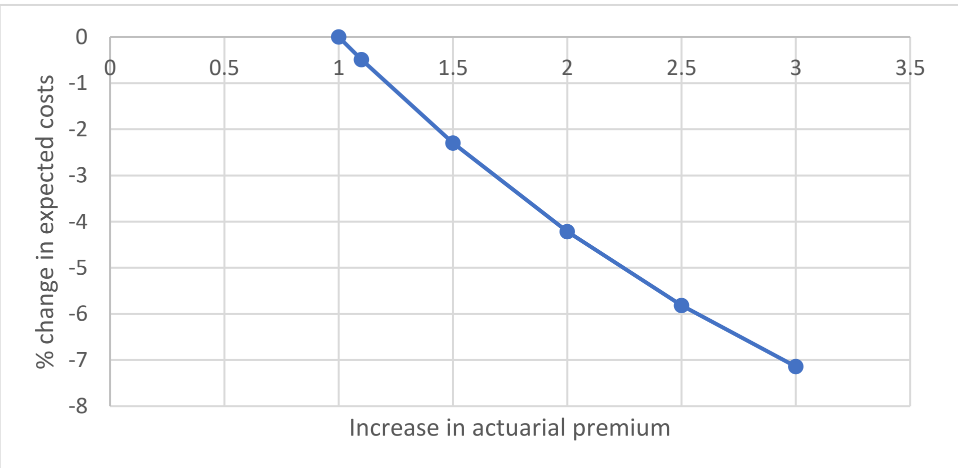

Figure D.5. Impact of actuarial prices on expected costs

premiums/levy rates has been estimated to reduce the probability of vessel inspection (needed to achieve ALOP) from $\beta = 0.358$ (one vessel in 2.8 inspected) to $\beta = 0.295$ (one vessel in 3.8).

6.5 Trade implications

Australia's biosecurity system operates under competing government priorities: protecting the nation's high biosecurity status — which underpins agricultural exports and environmental integrity — while simultaneously promoting trade and reducing regulatory barriers. These goals can be in conflict because greater trade openness and deregulation can heighten the risk of pest and disease incursions. Indeed, because biosecurity management imposes costs on inbound vessels/goods, it can be misused as a non-tariff barrier. To avoid this situation, the WTO sanctions biosecurity interventions intended to achieve ALOP. This benchmark is based on technical risk assessment that is somewhat subjective and non-transparent (Bland et al., 2024). In a decentralised biosecurity system, compliance with WTO principles could be determined by assessing four interventions made by the biosecurity authority:

i. *Efficient pricing of biosecurity risk* – Premiums/levy rates set too high would constitute a tax on imported goods/services and shipping services and would be regarded by the WTO as a non-tariff barrier. Given that the objective of actuarial science is to reveal the efficient price of risk, the focus of the WTO's interest would be on the actuarial methodology applied to set biosecurity risk insurance premiums/actuarial levy rates. Comparisons between biosecurity risk insurance premiums/actuarial levy rates applied by different countries, if they become available, would also be a useful reference point for the WTO.

ii. *Costs-reflective vessel inspection charges* – Over- or under-inflation of vessel inspection costs will also distort trade patterns suggesting that visibility over vessel inspection costs imposed by the biosecurity authority would be of interest to the WTO.

iii. *Optimal fine* – The analysis (based on example data) suggests that a fine on false signalling will be an important component of the biosecurity system. Our analysis suggests that fines for false signalling are analogous to a Pigouvian tax and should be set at the marginal damage that false signalling imposes on other vessel operators. Although further work will be needed to estimate the optimal fine, the principles for doing so are well-established in the point-source pollution domain and can be readily observed by the WTO.

iv. *Optimal probability of vessel inspection* – The research reported in this document identifies a methodology for setting the probability of vessel inspection. This involves identifying the optimal fine set at the marginal negative externality cost, and then identifying the probability of inspection needed to achieve an information efficient/incentive compatible biosecurity system. These principles are reasonably transparent.

These assessment criteria have significant advantages over the current approach involving a determination of whether biosecurity interventions are set at an "appropriate" level. Determining whether the price of biosecurity risk is efficient, vessel inspection charges are cost-reflective, and the severity of fines/probability of vessel inspection settings are optimal, can all be based on well-established principles, are more transparent, and can be informed by inter-country comparisons. This suggests that a decentralised approach to biosecurity would be of interest to the WTO. Furthermore, the method established in this report to compare a biosecurity system based on an appropriate level of protection with the efficient level of protection should also be of interest as a broad indicator of whether a biosecurity system represents embedded non-tariff barriers.

6.6 Distribution, economic efficiency and equity implications

An insurance approach to biosecurity effectively redistributes loss exposure arising from exotic threats from taxpayers in the importing country (the current approach) to the creators of biosecurity risk (vessel operators). In the Australian context, this could represent a redistribution of around $800m/year from consolidated revenue to the shipping industry. The distributional impact of an insurance approach to biosecurity must, however, be considered in light of: i) the biosecurity risk insurance premium will be distributed between shippers and consumers according to market power at any point in time; and ii) the economic efficiency implications noted in Section 5 where it was shown that substantial cost savings could be expected. Specifically, an insurance approach would substantially lower the cost of biosecurity where national biosecurity objectives are defined in economic efficiency terms, rather than as an arbitrary risk target. These results suggest that whilst an insurance mechanism would increase shipping costs, the net economic effect would be to increase welfare in the Australian economy.

7. Conclusions

This paper frames biosecurity as a missing market problem. Following the development and application of an actuarial methodology for pricing biosecurity risk, we focus on the rules and processes needed to implement a market for biosecurity risk insurance/actuarial levy mechanism in the biofouling domain. This approach to biosecurity is fundamentally different from the current approach in which the biosecurity authority manages risk through regulation of risk-creators. In contrast, a market for biosecurity risk insurance/actuarial levy mechanism is a decentralised mechanisms that expose risk-creators (vessel operators in this instance) to the financial consequences of their decisions and actions. Four interventions are needed to implement this approach: i) actuarial pricing of biosecurity risk; ii) a risk rating process for inbound vessels; iii) truthful revelation of information needed to determine risk status; and iv) an incentive-compatible payoff structure.

This report demonstrates how these design principles can be implemented by the biosecurity authority, through a biosecurity risk insurance/actuarial levy mechanism, to achieve ALOP. It also demonstrates how an alternative biosecurity strategy could be implemented to achieve an efficient level of protection. A key finding of this research is that these (or other) biosecurity objectives can be implemented through two control variables: the *probability of vessel inspection*, and *fines* for vessel operators that falsely signal information needed to determine the risk rating. We argue that the biosecurity authority should set the fine at the marginal damage cost that false signalling imposes on the market/mechanism (as a Pigouvian tax) and then set the probability of inspection so that the dominant strategy of vessel operators is to implement the stated biosecurity objective. Although not analysed in this report, revenue collected from fines for false signalling could be used to compensate vessel operators who truthfully signal biosecurity status but are required to undertake vessel inspection.

This methodology could be used to implement both the current objective (ALOP) requiring the biosecurity to formally define ALOP in terms of its preferences over vessel entry pathway. It could also be used to implement any alternative biosecurity objective including an efficient level of protection. ELOP relies on the decisions of vessel operators, considering all relevant costs including the expected loss exposure from biosecurity risks, to identify the optimal level of biosecurity effort. Based on a simplistic model of this approach to biosecurity, a significant improvement in economic efficiency could be expected from ELOP compared with ALOP defined as a requirement for all vessels to invest high-effort in biosecurity mitigation.

Economic efficiency gains arise because: biosecurity risk is priced in a way that creates incentives to reduce Australia's exposure to biosecurity risk; rules and processes are introduced to mitigate unwanted strategic behaviours, such as false signalling, that otherwise impose costs on all vessel operators; and private information held by vessel operators is utilised to identify the best responses to biosecurity threats. If these findings hold more generally, a biosecurity system implemented through decentralised mechanisms (a market for biosecurity risk insurance contracts or an actuarial levy) can be expected to be attractive to vessel operators as it results in lower expected costs.

It will be necessary to explore the potential for economic efficiency gains — both in this setting and in domains where direct costs, such as vessel delays, are smaller. Decentralised approaches that reveal hidden information and leverage operator-driven cost-saving strategies may improve efficiency and effectiveness. Now that an insurance approach has been developed for one domain — including actuarial methods, application, and market design — we have a clearer understanding of what's involved in applying this model more broadly, and the associated development and transition costs. These benefits should be weighed against those of existing systems or lower-cost alternatives to ensure the investment is justified.

The report identifies a range of refinements that will need to be incorporated into the economic structure of the market for biosecurity risk insurance/levy mechanism including: incentives linked to vessel reputation, expansion of the types of vessels with respect to the level of biosecurity effort, more complex vessel audit/inspection regime; and the implications of systematic (un-priced) risk. More complex economic models of the biosecurity system will need to be developed to analyse these refinements. However, once developed, this model will provide many practical insights into the creation and management of a more efficient, efficacious, and financially sustainable biosecurity system.

While the research reported in this paper applies to biofouling, the actuarial and economic principles described apply to other activities that create biosecurity risk including from imports and inbound passengers. The market structure needed for these domains of biosecurity will be adaptations of the mechanism described in this paper. The application of actuarial methods to price these biosecurity risk, and research into the information and incentive architecture needed to implement a market for biosecurity risk insurance contracts/actuarial levy on risk-creators should mark a fundamental change in the way biosecurity risk is managed in the economy.

A decentralised approach to biosecurity exposes and clarifies the biosecurity interventions that could be misused as non-tariff barriers (i.e., efficient pricing of risk, cost-reflective inspection costs, optimal fine structure, and incentive compatible vessel inspection probability) for which there are well-developed assessment criteria, increased transparency, and scope for inter-country comparisons. Given the novelty of the biosecurity risk insurance approach, it will be important to gain legal advice with respect to its status under WTO rules.

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Appendix E: Biofouling Insurance Pricing with Probabilistic Risk Analysis — Methodologies

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Biofouling Insurance Pricing with Probabilistic Risk Analysis – Methodologies

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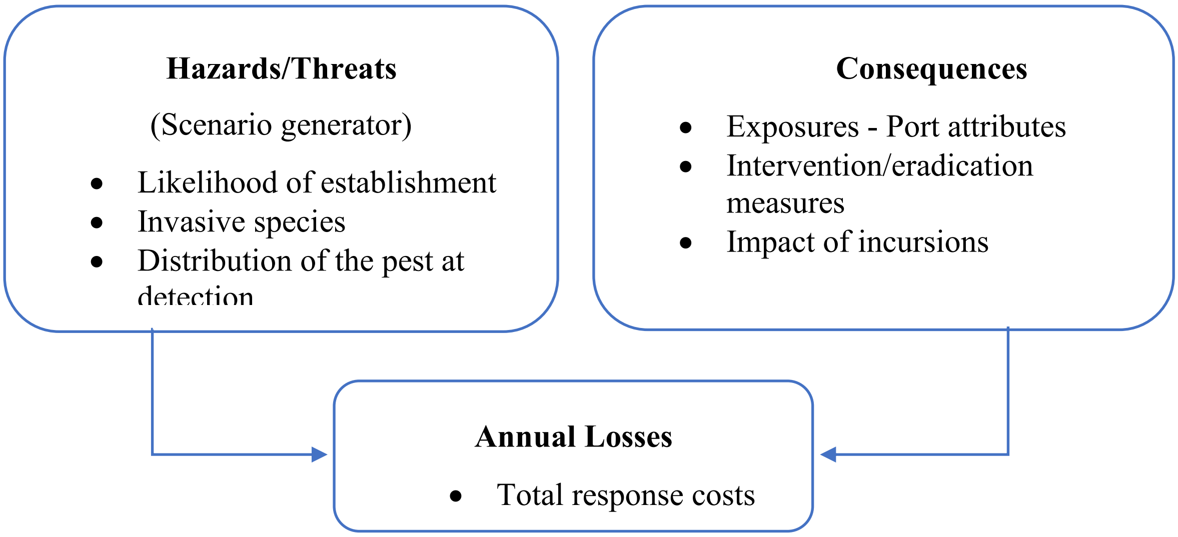
2023

1. Developing a probabilistic approach to biofouling risk analysis

1.1 Overview

Biofouling is defined as non-indigenous marine species (NIMS) incursions that may or may not require intervention or eradication. The risk analysis utilises incursion scenarios to assess the threat of various NIMS at different ports, the vulnerability of those ports to the incursions, and the annual losses (cost of eradication/containment) of successful NIMS establishments. The overall risk of any given incursion scenario reflects all three of these factors. An illustration of the risk analysis framework is shown in the Figure below.



Hazard/Threat

The hazard module generates various scenarios of NIMS incursions and estimates the likelihood of different scenarios based on expert judgment, assuming that an incursion has occurred. Crombie et al. (2008) develop hypothetical marine pests and incursion scenarios to quantify the relationship between the cost and likelihood of successful eradication of NIMS. Twenty-one incursion scenarios are created by Crombie et al. (2008) based on the combination of the following three types of variables:

- Species: Biological attributes of the pest species

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- Distribution: Details of the pest's distribution, reflecting on the level of establishment
- Location: Characteristics of the area or location of the incursion

These variables are believed to influence the cost and likelihood of the successful eradication of marine pests. In addition, we extend their scenarios by considering additional variables as listed below:

- Amount of manmade structures at the incursion location to reflect the extent of anthropogenic activities
- Water temperature and salinity at the incursion location

A probabilistic risk analysis requires the probability associated with each of the generated scenarios. The likelihood of incursion scenarios is not discussed in Crombie et al. (2008) and thus needs to be estimated in this project. Existing literature, such as Hewitt (2011), estimates the overall NIMS establishment rate per year but does not consider how this rate is related to specific incursion scenarios. Port attributes and the number of ships arriving at each port affect the probability of an incursion scenario and thus need to be gathered. Expert judgement also needs to be elicited to assign probabilities to each incursion scenario.

Consequences

The consequence of an incursion in this project refers to the response cost incurred. Consequences can be affected by various factors, such as the location of the incursion, the impact of the NIMS, and the guidelines for response measures. There are three possible responses: eradication, containment, or taking no action. The decision process follows the guideline set out in the Australian Emergency Marine Pest Plan (EMPPlan) Rapid Response Manual[4]. The response may also change after taking initial actions. A study of the technical feasibility of eradication and a cost-benefit analysis is required to determine the best responses.

Therefore, to determine the consequence of an incursion, we need to know which action will be taken and the subsequent cost. Crombie et al. (2008) built a regression model to link the likelihood of successful eradication with the eradication cost given the relevant variables of an incursion. However, the technical feasibility of eradication is not examined. To model the consequence of an incursion, we take the following steps:

1) Given an incursion scenario, we first elicit expert opinion on whether it is technically feasible to eradicate the pest.
2) For all the scenarios considered in the expert elicitation, we assume that actions will be taken. If feasible to eradicate, we utilise the regression model estimated by Crombie et al. (2008) to determine the eradication cost. If not, we estimate the containment cost instead.

It's worth noting that the real-world scenario can be significantly more complex, potentially necessitating a combination of eradication and containment efforts.

An evidence-based study on the technical feasibility of eradication has been provided by Drolet et al. (2015). However, of the 143 case studies examined in their paper, only 25 pertain to marine pest incursions, with the remainder focusing on freshwater pest incursions. Consequently, the model estimated in their paper does not align with the scope of our research.

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[4] https://www.marinepests.gov.au/sites/default/files/Documents/empplan-rapid-response-manual-generic_0.pdf

Annual Loss

The probability distribution for the annual loss from incursions is determined by the following factors:

1) The number of incursions
2) The hazard scenario for each incursion and the associated consequences

Note that the expenses for monitoring biofouling risk are not considered in the loss. They will be treated separately in the pricing. In the hazard and consequence modules, we have established the distribution of the consequences of an incursion. Hewitt (2011) estimates 4.9 establishments of NIMS per year and that 5.49% of the established species are of biofouling concern. We assume that only species of biofouling concern will lead to an action of eradication or containment. Therefore, the number of incursions leading to actions follows a distribution with a mean value of 0.2.

The distribution of annual loss will be used to determine the expectation and variance of annual loss and other statistics that will be useful in not only insurance pricing but also budgeting and risk management. It is also straightforward to incorporate any cap imposed on the claims into the annual loss calculation.

1.2 Expert elicitation

1.2.1 Information requiring expert elicitation

Expert elicitation is employed to determine two important components required in constructing the loss distribution:

1) Likelihood of incursion scenarios given that an incursion has occurred
2) Technical feasibility of eradication for incursion scenarios

We make a simplified assumption that eradication will take place whenever it is technically feasible.

In a typical insurance pricing application, the probability of an insured event is estimated from historical claim data. However, NIMS events have catastrophic risk features with high severity but low frequency, hence available data are insufficient to obtain a probabilistic distribution of incursion likelihood.

Instead, this report considers expert elicitation for the estimation of likelihood, where experts are asked to judge the probability of given scenarios. Since assigning absolute probabilities can be challenging, given their small magnitude, we assess their relative likelihood instead. The absolute likelihood of an incursion scenario can be derived from the relative likelihoods, assuming that we can construct a complete set of incursion scenarios.

1.2.2 Survey design

To conduct the expert elicitation, we designed a survey based on the twenty-one incursion scenarios developed by Crombie et al. (2008) for the estimation of response costs. Each scenario is a combination of variables from three categories: species attributes, species distribution attributes and incursion location attributes. The original scenarios were created in collaboration with CRC Reef and CSIRO and are believed to reflect potential real-life situations. Therefore, we decide to retain all original variables and scenarios. We further extend the twenty-one scenarios by considering additional variables relevant to incursion likelihood.

Water temperature and salinity. Since some marine species may not be able to establish themselves in certain environments, it is important to incorporate water temperature and salinity at the incursion location when considering establishment likelihood. We consider three ranges for temperature with reference to the suitable living temperature range of major invasive pests.

Length of manmade structures. Manmade structures can provide a habitat for NIMS, hence increasing incursion likelihood for certain species. Glasby et al (2007) found that the degree of artificial objects exposed to water at a port may contribute to the likelihood of the successful establishment of NIMS. The number of manmade structures is also an indicator of anthropogenic activities which may increase the likelihood of an incursion. We use the total length of manmade structures in direct contact with water as the metric since infrastructure in these areas contributes most significantly to biofouling.

Details for all variables are presented in the three tables below. Table E.1 includes species-specific information, Table E.2 includes details about incursion characteristics, and Table E.3 includes location-related details.

Table E.1. Species Variables

SPECIES INFORMATION		
Variable	**Description**	**Levels**
Size of organism	Do mature organisms have maximum diameter less than or greater than 5 cm?	Small: < 5 cm Large: > 5 cm
Appearance	Is the organism hard to locate due to cryptic behaviour or appearance such as burrowing or hiding, prone to overgrowth by other organisms/ camouflage or nocturnal habit?	Cryptic Obvious
Habit	Solitary organisms are motile and tend to be spread randomly through their habitat — for example some species of fish, jellies, crabs. Grouped organisms will typically be found in clumps or patches. They may be either individuals which aggregate or colonial organisms.	Solitary Grouped
Preferred habitat	Is the organism pelagic or benthic and if benthic, what type of substrate does it prefer?	Pelagic Benthic, hard substrate Benthic, soft substrate Benthic, hard and soft substrate
Larval duration/ Incubation period	The expected time from introduction of larvae to the water column to settlement, or time from formation of eggs to hatching	Short: hours–days Medium: days–weeks Long: weeks–months
Time to maturity	The expected time from settlement or hatching to reproductive maturity.	Short: <2 months Medium: 2–12 months Long: > 1 year
Propagules per reproductive event	Expected number of propagules per mature organism per sexual reproductive cycle.	Low: <10 000 Mod: 10 000–1 000 000 High: >1 000 000
Sexual reproductive cycles per year	Number of spawning or other reproductive periods per year.	Annual ; Biannual More frequent / continuous
Asexual reproduction	Is the organism capable of asexual reproduction?	Yes No

Table E.2. Incursion Distribution Variables

CURRENT DISTRIBUTION		
Variable	**Description**	**Levels**
Area currently infested	The area currently infested by the pest. This includes the areas in which the pest has been found during the delimitation survey as well as the area between non-contiguous locations. (1 hectare (ha) is equal to 10 000 m^2)	Very small: < 100 m^2 Small: 100 – 1000 m^2 Medium: 1000 – 10 000 m^2 Large: 1 – 10 ha Very Large: > 10 ha
Profusion	A measure of the level of establishment of the pest. Individual organisms (solitary or aggregating) will typically be 'countable'. Colonial organisms may more readily be described by the area in which they have attained maximal density.	For 'countable' organisms: Low: <100 Mod: 100-1000 High: >1000 For area-covering species: Low: <10 Mod: 10-100 High: >100
Pattern	Are organisms continuously or randomly scattered throughout their range, or do they tend to 'clump'? And if they clump, how many clumps have they formed in this area?	Continuous Less than 5 patches 5 or more patches
Utilization of suitable habitat	What proportion of the suitable habitat in the area is the organism established in? (Suitable habitat is defined in the variable "Preferred habitat")	Low: < 10% Moderate: 10-50% High: > 50%
Maturity of organisms found	Does the infestation consist of juvenile organisms only or have some reproductively mature organisms been found?	Juveniles only Adults
Maximum depth of infestation	The maximum depth the species was recorded at during the delimitation survey.	< 2m 2 – 15m > 15m

Table E.3. Location Variables

LOCATION FACTS		
Variable	**Description**	**Levels**
Max depth of suitable habitat	The maximum depth of suitable habitat in the area. See also Maximum depth of infestation	< 2m 2 – 15m > 15m
Turbidity	A measure of the amount of suspended matter in water, and by extension, of water clarity.	Clear: visibility >5m Moderate turbidity: Visibility 1-5m High turbidity: Visibility <1m
Water exchange rate	Rate of exchange of water between the affected area and surrounding areas. **Minimal exchange** refers to areas such as marinas whereby natural or manmade means a body of water is effectively isolated. **Low exchange** applies to areas such as estuaries or buoys with narrow openings which will limit flows of water in and out of the area. **High exchange** suggests there are no significant restrictions on water flowing through the area. This may apply to open ocean or ports in wide open bays.	Minimal exchange Low exchange High exchange
Mean temperature range	Monthly mean water temperature range measured in the infested area	10 – 20°C 15 – 25°C 20 – 30°C
Salinity	Mean monthly water salinity profile measured in the infested area (parts per thousand, ppt).	Numeric, continuous (ppt)
Tidal range	Mean monthly tidal range measured in the infested area, calculated as Mean High Water (MHW) – Mean Low Water (MLW)	Numeric, continuous (m)
Manmade structures	The total length of manmade structures in direct contact with water, such as piers, berths, quays, jetties, and breakwaters, in the infested area.	Low: <500m Mod: 500m-1500m High:>1500m

We also design the scenarios in a way such that most of their location attributes match the characteristics of the selected six Australian ports. The names and relevant attributes of the six ports are given in Table E.4. Maximum depth and Temperature have been categorized into reasonable ranges.

Table E.4. Selected Six Ports

Port Name	Mean temperature range	Maximum Depth	Tidal range	Salinity
Port Hedland	20-30	> 15m	6	34
Port Melbourne	10-20	2m-15m	0.4	35.7
Port Brisbane	15-25	2m-15m	1.63	35
Port Townsville	20-30	2m-15m	3.8	35
Port Fremantle	15-25	2m-15m	0.7	36
Port Darwin	20-30	2m-15m	3.7	33

We have developed a set of 31 incursion scenarios. These scenarios encompass a total of 7 hypothesised species, with each species represented in 4 to 5 unique incursion cases. The variables pertaining to distribution and location closely mirror the environmental features of selected Australian ports. This represents an increase of ten scenarios compared to the study by Crombie et al. (2008). The additional scenarios aim to enhance the range and diversity of our responses, thus aiding the construction of a more robust model. In each survey question, we place two scenarios (scenario A and scenario B) side by side and ask experts to estimate the relative likelihood of the two scenarios. We also ask experts to estimate the technical feasibility of eradication for each scenario.

The objective of the survey is to show how information from existing marine science studies can be amalgamated into insurance pricing. We acknowledge that new practices and knowledge may have become available to construct more realistic scenarios since the publication of Crombie et al. (2008). To obtain a more accurate analysis, more effort and expertise should be devoted to constructing these scenarios.

Furthermore, our survey also collects information on the expert's field of expertise and year of experience in the field. Detailed survey questions and scenarios will be provided.

1.2.3 Survey participants

The participation group includes the following biofouling stakeholders[5]:

- Scientists specialising in marine science and biofouling risk
- Government officials involved in managing biofouling risk
- Private sector specialists who work in biofouling risk, inspections and related analyses.

Both Australian and international participants are expected.

1.3 Linear mixed model for the relative likelihood of incursion scenarios

1.3.1 The linear mixed model

Denote K as the number of variables used to construct the incursion scenarios, and M as the total number of scenarios. In our survey, $K = 20$, and $M = 31$. Let $x_{k,i}$, for $k = 1, \ldots, K$, and $i = 1, \ldots, M$, represent the value of the k-th variable in the i-th scenario. The relative likelihood of two scenarios i and j evaluated by expert v is represented by $l_{i,j,v}$.

A linear mixed model is used to model the log relative likelihood of two scenarios, expressed as follows:

$$\ln(l_{i,j,v}) = \sum_{k=1}^{K} (x_{k,i} - x_{k,j}) b_k + c_v + \epsilon_{i,j,v} \tag{1}$$

where b_k is the coefficient for the kth variable, c_v is the expert-specific random effect, and $\epsilon_{i,j,v}$ is the error term. We further assume that $c_v \sim N(0, \sigma_c^2)$, and $\epsilon_{i,j,v} \sim N(0, \sigma_\epsilon^2)$.

The fixed effect coefficient b_k measures how much the difference in the kth variable between two scenarios impacts the relative likelihood of the two scenarios. The expert-specific random effect captures the variation of likelihood assessments between different experts. The

[5] University of Melbourne Human Ethics ID: 2023-27400-42497-3

experts who respond to the survey are a sample of a larger expert population. The distribution of c_v informs us of the extent of variation to be expected if a different sample of experts were to respond to the survey.

1.3.2 Weighing responses by experts' year of experience

We further extend the above model to accommodate different weights for the responses from different experts. Our survey collects the number of years of experience of expert v from a relevant field, which we denote by g_v. The idea is that the more experience an expert has, the more weight their response will be given. The weights can be incorporated into the model by multiplying the variance of the error term with the inverse of the years of experience. Accordingly, the error term for the observation $l_{i,j,v}$ is assumed to follow $\epsilon_{i,j,v} \sim N(0, \frac{\sigma_\epsilon^2}{g_v})$.

Similarly, we can also apply different weights to responses depending on the field of expertise of the expert if we believe certain fields are more relevant.

1.3.3 Allowing different variances among individual experts

We can also allow the responses from experts to have individual variances. To do so, we assume $\epsilon_{i,j,v} \sim N(0, \sigma_{\epsilon,v}^2)$, where $\sigma_{\epsilon,v}^2$ is the variance for expert v. The values of $\sigma_{\epsilon,v}$, for $v = 1, \dots, V$, can be estimated simultaneously with the other parameters in the model.

1.4 Generalised linear mixed model for the technical feasibility of eradication

Since the response cost differs for eradication and containment, our survey asks experts whether eradication is technically feasible for each scenario. A generalised linear mixed model can be built to classify the technical feasibility. We categorise the responses received by the experts into two levels: likely or unlikely. The response of expert v for scenario i is denoted by $y_{i,v}$, and is described by a generalised linear mixed model. In more detail, $y_{i,v}$ is assumed to follow a Bernoulli distribution with a success probability of $q_{i,v}$. Here, $q_{i,v}$ represents the probability of eradication for scenario i evaluated by expert v. The success probability is further modelled as follows:

$$\ln\left(\frac{q_{i,v}}{1 - q_{i,v}}\right) = d + \sum_{k=1}^{K} x_{k,i} e_k + f_v + \varepsilon_{i,v}, \tag{2}$$

where d is the intercept, e_k is the fixed effect of the kth variable, f_v is the expert-specific random effect, and $\varepsilon_{i,v}$ is the error term. We assume that $f_v \sim N(0, \sigma_f^2)$, and $\varepsilon_{i,v} \sim N(0, \sigma_\varepsilon^2)$.

1.5 Model selection

A large number of parameters are present in the models built for relative likelihood and technical feasibility, potentially leading to overfitting problems and masking the importance of some variables. We consider a stepwise approach to select the predictors to be used in the final model. The approach we take is a backward elimination of random-effect terms followed by backward elimination of fixed-effect terms in both linear mixed models.

1.6 The absolute likelihood of incursion scenarios

In theory, we can construct many incursion scenarios by varying the values assumed for each of the scenario variables. However, not all combinations are reasonable. For example, certain species may not live at a certain depth of habitat. Despite this, in order to determine insurance prices, we construct scenarios using all the significant variables in the relative likelihood model, technical feasibility model, and cost estimation model, without considering the biological reasonableness of each scenario. Suppose that this process leads to the construction of M scenarios. We evaluate the relative likelihood of each scenario with respect to the reference scenario which is the first constructed scenario.

Let us denote the absolute likelihood of the reference scenario and scenario i, given the occurrence of an incursion, by p_0 and p_i, respectively. The relative likelihood of scenario i with respect to the reference scenario without knowing which expert makes the assessment follows a lognormal distribution based on the linear mixed model shown in Equation (1). The distribution can be expressed as follows:

$$\ln\left(\frac{p_i}{p_1}\right) \sim N\left(\sum_{k=1}^{K}\left(x_{k,i} - x_{k,1}\right)b_k\,, \sigma_\epsilon^2 + \sigma_v^2\right)$$

As a result, the expectation of the absolute likelihood of scenario i, p_i, can be estimated as follows:

$$E\left(\frac{p_i}{p_1}\right) = e^{\sum_{k=1}^{K}(x_{k,i}-x_{k,1})b_k+\frac{\sigma_\epsilon^2+\sigma_v^2}{2}}\,. \tag{3}$$

Since p_i represents the probability of scenario i taking place given that an incursion has occurred, the probabilities of all M scenarios add up to 1. Therefore, we have

$$p_1 = \frac{1}{\sum_{i=1}^{M} E\left(\frac{p_i}{p_1}\right)},$$

$$p_i = \frac{E\left(\frac{p_i}{p_1}\right)}{\sum_{i=1}^{M} E\left(\frac{p_i}{p_1}\right)},$$

where $E\left(\frac{p_i}{p_1}\right)$ is computed from Equation (3).

We note that the relative likelihood is assessed under the assumption that each incursion location has the same vessel traffic, such that the impact of vessel traffic does not dominate. To incorporate the impact of vessel traffic at ports on incursion likelihood, we simply multiply the relative risk of a scenario by the ratio of vessel traffic at incursion locations between this scenario and the reference scenario.

1.7 Response costs

1.7.1 Eradication or Containment

Given the occurrence of an incursion, we assume that there are two possible actions - eradication and containment and the decision is governed by the technical feasibility of eradication. If the estimated feasibility exceeds the pre-specified threshold, say 0.5, the predicted action for scenario i is eradication and $y_i = 1$. Otherwise, the predicted action is containment and $y_i = 0$.

1.7.2 Eradication cost

The cost of eradication is estimated using the cost estimation tool provided by Crombie et al. (2008). Given the variables relating to the specific incursion, we determine the estimated eradication cost targeting a 95% eradication success rate. Let us denote the estimated eradication cost for scenario i by EC_i.

Crombie et al. (2008) find four variables significantly affecting the eradication costs:

- Area Infested
- Retention
- Depth of Available Habitat
- Habit

The eradication cost can be estimated using the following formula:

$$ln(\widehat{EC_i}) = \hat{\alpha} + \sum_{k=1}^{K} x_{k,i}\hat{\beta}_k,$$

where $\hat{\alpha}$ is the estimated intercept and $\hat{\beta}_k$ is the estimated coefficient for the kth predictor. The estimated intercept and the coefficient for the significant predictors are provided in Table E.5.

Table E.5. Parameter Estimates for the Eradication Cost Model (Source: Crombie et al. 2008)

Factor / Level	Coefficient	std.error	p-value
Intercept	13.629	0.5756	< 0.0001
Area / Very Small	0		
Area / Small	0.848	0.2820	0.0026
Area / Medium	1.084	0.3058	0.0004
Area / Large	2.472	0.3126	< 0.0001
Retention / Minimal Exchange	0		
Retention / Low Exchange	0.315	0.2550	0.216
Retention / High Exchange	1.573	0.2883	< 0.0001
Depth Available / < 15m	0		
Depth Available / > 15m	1.038	0.2268	< 0.0001
Habit / Grouped	0		
Habit / Solitary	0.676	0.2541	0.0078

1.7.2 Containment cost

The cost of containment is estimated using the results from Summerson et al. (2013). In this report, containment control is the application of control that aims to contain the pest population within the port where the infestation is detected. The total containment cost within the initial port of infestation encompasses several components including the costs associated with vessel inspection and cleaning, ballast water exchange, and port infrastructure maintenance.

It is assumed that each recreational vessel undergoes an inspection and cleaning biannually. In contrast, commercial vessels are exempt from these procedures as rigorous inspection protocols are already in place for them. The cost of inspecting vessels was determined by considering the daily inspection cost and the daily traffic data. Inspection of each vessel is priced at $1000 per day. The daily traffic is estimated to be 12.5% of the total port capacity.

The cost for cleaning the vessels was computed by multiplying the daily cleaning cost, which is also $1000, with the number of infected vessels. It is assumed that infected vessels account for 20% of the daily traffic or equivalently 2.5% of the port capacity. Based on these calculations, the annual expense for Darwin Port, which comprises 518 marina berths, is approximately $77,000. In certain cases, such as the Port of Melbourne, the port may only facilitate commercial vessels and not have any marina berths available. In such scenarios, we assume that no vessel inspection and cleaning costs will be incurred.

The cost for ballast water exchange was derived from a 2007 estimate by the CIE, which placed the cost at $24,000,000 per year for the entirety of Australia. This figure was divided by the number of ports participating in the ballast water exchange program (129 ports according to Hayes et al., 2009) resulting in an annual cost of $214,315 per port (adjusted to 2012 dollars).

Due to differences in port infrastructure, the cost of control and maintenance was calculated separately for each of the case study ports in Summerson et al. (2013). For our study, we assume that the cost of port infrastructure maintenance is proportional to the amount of manmade structure or vessel traffic. We use the Darwin and Cairns ports studied in Summerson et al. (2013) as the reference. Darwin port's maintenance cost is $40,800 while that for Cairns port is $48,200.

The containment cost is calculated as the present value of the cost for ongoing management and control in a given port over the containment horizon. Mathematically, the containment cost can be expressed as follows,

$$CC = \sum_{t=1}^{T} (1+r)^{-t} ACC_t,$$

where ACC_t is the annual containment cost in year t, r is the risk-free interest rate, and T is the containment horizon.

Since different port attributes, which may affect containment costs, are used in the incursion scenarios, let us denote the estimated containment cost for scenario i by CC_i.

1.7.3 The response cost

After obtaining the eradication cost and containment cost for each scenario, the response cost for scenario i can be expressed as follows:

$$C_i = y_i EC_i + (1 - y_i) CC_i$$

The distribution of C_i given q_i can be easily derived.

y_i	0	1
C_i	CC_i	EC_i
Probability	$1 - q_i$	q_i

The expectation and variance of the response costs are shown below:

$$E(C_i) = q_i EC_i + (1 - q_i) CC_i$$
$$E(C_i^2) = q_i EC_i^2 + (1 - q_i) CC_i^2$$
$$Var(C_i) = E(C_i^2) - [E(C_i)]^2$$

1.8 The distribution of the response cost

In the previous sections, we have described how to obtain the absolute likelihood and the distribution of the response costs given a specific incursion scenario. Now we can combine the two components to obtain the distribution of response cost given that an incursion has occurred. Let us denote the response cost by C, which is a discrete random variable with the following distribution:

$$P(C = C_i|C_i) = p_i.$$

We can obtain the following expectation and variance for the conditional random variable $C|C_i$:

$$E(C|C_i) = \sum_{i=1}^{M} p_i C_i \, ,$$
$$Var(C|C_i) = \sum_{i=1}^{M} p_i C_i^2 - \left(\sum_{i=1}^{M} p_i C_i \right)^2 .$$

We can also express the distribution of C which takes discrete values $\{CC_1, EC_1, CC_2, EC_2, \dots, CC_M, EC_M\}$, as follows:

$$P(C = CC_i) = p_i(1 - q_i),$$
$$P(C = EC_i) = p_i q_i.$$

The expectation and variance of the unconditional random variable are shown below:

$$E(C) = \sum_{i=1}^{M} p_i E(C_i) \, ,$$
$$Var(C) = \sum_{i=1}^{M} p_i E(C_i^2) - \sum_{i=1}^{M} \big(p_i E(C_i)\big)^2 - \sum_{i=1}^{M} \sum_{j=1}^{M} p_i p_j E(C_i) E\big(C_j\big).$$

1.9 Annual loss

In the previous section, we have built the distribution of the response cost for an incursion. The annual loss from all the incursions can be expressed as follows:

$$L = \sum_{j=1}^{J} C^{(j)},$$

where J is the number of incursions in the year and $C^{(j)}$ represents the response cost for the jth incursion.

Hewitt et al. (2011) estimate that the current establishment rate of 4.9 NIMS/year and between 69.2% and 82.9% of NIMS establishments will have an association with biofouling. This provides a range of establishment rates between 3.39 and 4.06 NIMS/year that are anticipated to have a biofouling association. The authors also estimate that 5.42% of NIMS is likely to be biofouling Species of Concern. "Biofouling Species of Concern" typically refers to specific species that are particularly problematic in a biofouling context. These may be species that are very effective at colonising surfaces, that have harmful effects on the surfaces they colonise, or that are invasive and can cause ecological harm if they are transported to new regions through biofouling. We assume that the incursion of such species guarantees a response, either containment or eradication. Therefore, an average of 0.18-0.22 NIMS incursions per year would lead to a response.

The random variable J is subsequently assumed to follow a Poisson distribution with a mean of 0.2, i.e.

$$J \sim \text{Poisson}(0.2).$$

As a results, the annual loss from all incursions follows a compound Poisson distribution. The mean and expectation of the annual loss can be expressed as follows:

$$E(L) = 0.2E(C),$$
$$Var(L) = 0.2\left[\left(E(C)\right)^2 + Var(C)\right].$$

We are aware of the high uncertainty in the estimated establishment rate and the critics of the method used by Hewitt et al. (2011). Therefore, we will further consider other establishment rates in the range of 0.1-1.

2. Vessel risk assessment

2.1 Relative risk of vessels

2.1.1 Relative risk and absolute risk

The annual loss estimated in the previous section is the total amount caused by all the vessels coming into an Australian port in a given year. Since it is infeasible to trace an incursion to a specific vessel, we cannot directly attribute the annual loss to specific vessels.

To evaluate the distribution of losses caused by a vessel, we first determine the probability that a vessel's movement leads to an establishment given that an incursion has occurred. Barry et al. (2015) developed a risk assessment tool to determine the relative risk of introducing incursion for each vessel. A model is built relating the risk to the vessel and voyage characteristics and the environmental features of donor and recipient ports. Because of the lack of relevant data, the model is estimated using expert elicitation about the relative risk.

Let s_i be the probability of an establishment occurring from the ith vessel. The relative risk of the ith vessel, rr_i, is defined as follows:

$$rr_i = \frac{s_i}{s_1}, \text{for } i = 1,2,\dots,I,$$

where the 1st vessel is used as the reference and I represents the total number of vessels. rr_i can be estimated from the regression model built by Barry et al. (2015), given the values of predictors. However, the value of p_1 is still unknown. Given that $\sum_{i=1}^{I} s_i = 1$, we can calculate s_i as follows:

$$s_1 = \frac{1}{\sum_{i=1}^{I} rr_i} \text{ and } s_i = \frac{1}{\sum_{i=1}^{I} rr_i} rr_i.$$

Since the total number of incursions in a year follows a Poisson process with a mean of 0.2, the number of incursions caused by the ith vessel also follows a Poisson process but with a mean equal to $0.2s_i$.

2.1.2 Factors affecting the relative risk of vessels – Barry et al. (2015)

Barry et al. (2015) show that vessel risks are significantly affected by the following factors:

- Port type change between the port of last call and Australian 1st port of call (same, more enclosed, less enclosed)
- Absolute difference in mean temperature at the port of last call and Australian 1st port of call
- Absolute difference in mean water salinity at the port of last call and Australian 1st port of call
- Berthing duration
- Anti-fouling coating age (new, 50% of life span, 100% of life span)

In particular, the relative risk can be estimated as follows:

$$\ln(\widehat{rr_i}) = \sum_{h=1}^{H} (z_{h,i} - z_{h,1})\hat{\beta}_h,$$

where $z_{h,i}$ is the hth predictor that explains the relative risks of vessels, H is the total number of predictors, and $\hat{\beta}_h$ represents the estimated impact of the difference in the hth predictor values between two scenarios. The values of $\hat{\beta}_h$ for the significant predictors are shown in Table E.6. Given the predictor values for each vessel arriving in Australian ports, we can determine its relative risk.

Table E.6. Parameter Estimates for Vessel Relative Risks (Source: Barry et al., 2015)

Variable level	Value	Std. Error	t-value	p-value	Sig.
Port type change					
Same	0 (aliased)				
More enclosed	-0.08679	0.047882	-1.81252	0.070429	n.s.
Less enclosed	-0.33822	0.092462	-3.65798	0.000278	***
Absolute difference in mean temperature	-0.03484	0.006642	-5.24522	2.20E-07	***
Absolute difference in mean salinity	-0.01316	0.002501	-5.26362	2.00E-07	***
Anti-fouling					
New	0 (aliased)				
50% of service life	0.283862	0.068718	4.130828	4.15E-05	***
100% of service life	0.642734	0.058611	10.96603	1.57E-25	***
Berthing duration	0.013998	0.001532	9.138205	1.09E-18	***

n.s. – non-significant, * – *P<0.001***

2.2 Level of fouling (LOF) - In-water survey by MPI New Zealand

2.2.1 In-water survey findings

Ministry for Primary Industries (MPI) New Zealand conducted three in-water surveys to study/predict the level of fouling on vessels arriving in New Zealand ports. The resulting reports (Inglis et al, 2010; Morrisey et al, 2017; Atalah et al, 2022) investigate how predictors related to vessel classes and characteristics, maintenance history, and voyage history contribute to LOF.

Inglis et al. (2010) and Morrisey et al. (2017) find that the following predictors are important in identifying potential vessels with high fouling risk:

- Time since the last out-of-water maintenance
- Time since the last anti-fouling coating
- Number of ports visited in the last 12 months
- Maximum days of laid-up period since the last anti-fouling coating (AFC)
- Time since last survey

The two studies also reveal that the impact of these predictors on LOF differs between the following vessel classes:

- bulkers, general cargo and tankers
- container vessels
- ro-ro
- passenger vessels

Inglis et al (2010) employed a two-step methodology to formulate a model for LOF (Level of Fouling). Initially, they constructed Boosted Regression Trees (BRT) for varying response variables, including Biomass and Total Species Richness. They subsequently employed Partial Dependence Plots to scrutinise the impact of the most influential predictors. Following this, they developed a Linear Regression Model to link these response variables to LOF. However, their analysis indicated that the developed models exhibited suboptimal performance during cross-validation. In addition, the in-water survey data used in Inglis et al. (2010) also suffers from the data quality issue. Nonetheless, using these models, Inglis et al. (2010) proposed a set of criteria for identifying vessels potentially exhibiting high fouling risk.

Drawing on findings from a new in-water survey, Morrisey et al. (2017) introduced modifications to these criteria to enhance their accuracy in pinpointing high-risk vessels. Furthermore, a study by Atalah et al. (2022), which use a more recent in-water survey, demonstrated that the criteria revised by Morrisey et al. (2017) effectively identified high-risk vessels in a new dataset. Atalah et al. (2022) also built a new predictive model for Compliance with the CRMS short-stay criteria and suggested the following two options for identifying compliant/noncompliant vessels.

Option 1: Using a generalised linear model (logistic regression) to predict the compliance of a vessel. The estimated parameters are shown in Table 7.

Table E.7. Parameter Estimates of the Logistic Regression for Predicting Compliance (Source: Atalah et al. 2022)

Risk indicators	Odds Ratios	CI	p
(Intercept)	0.97	0.61 – 1.55	0.908
Av. Speed	0.32	0.17 – 0.54	**< 0.001**
Time since AF	9.56	4.88 – 21.97	**< 0.001**

Option 2: Assign high-risk level for all vessel types if time since antifouling treatment is > 320 days OR time since last out-of-water maintenance > 550 days.

A third option which assigns high-risk level by vessel types is also discussed. However, the authors recommend using the first two options due to the low sample size in each vessel type and the complexity of implementing the third option.

2.2.2 Applying in-water survey findings to assessing vessels' relative risk

The difficulty of applying the findings from the in-water survey studies lies in how to translate LOF or compliance/noncompliance to the probability of causing incursions, or what is the relative risk (numerically) of a vessel with high fouling risk and one with low risk. From the insurance pricing perspective, correctly categorising low-risk vessels is as important as high-risk ones in order to set the appropriate insurance premium. The model we use should have high sensitivity and high specificity in predictions. Therefore, we adopt the two options recommended by Atalah et al. (2022), which show reasonable prediction performance.

We considered two possible approaches to utilise the findings from Atalah et al. (2022).

1) Assume a constant for the relative risk between vessels with predicted compliance and those with predicted noncompliance. We will use different values for this constant to show how prices change with the choice.
2) Using the probability of non-compliance as the indicator of the probability of causing an incursion.

2.3 Averaging estimates from two studies

Barry et al. (2015) and the three reports from in-water surveys all find the age of AFC an important predictor. The two lines of studies complement each other in the following ways:

1) Barry et al. (2015) use expert elicitation while MPI studies use an evidence-based approach - in-water surveys.
2) Barry et al. (2015) incorporate berthing duration, and several port characteristics, including harbour type, water temperature, and water salinity. MPI studies have more emphasis on voyage history and vessel classes.

Given the complementary nature of the two lines of studies, we believe it is beneficial to combine the results from the two studies. A simple approach is to use the weighted average of the estimated relative risks from the two studies. We assign a 50% weight to each study, assuming that the two studies are of similar credibility and accuracy.

2.4 Data for assessing vessel risks

To use Equations (4) and (5) to determine the absolute risk for each vessel, we need to know the risk predictors for all the vessels arriving in Australia. The risk predictors we consider include significant predictors identified by Barry et al. (2015) and Atalah et al. (2022). As a result, we collect vessel type, port of last call, arrival port, berthing duration, time since last AFC, time since last out-of-water maintenance, and average speed for all vessels arriving in an Australian port from a foreign port in 2019.

In 2019, there were 28,584 port arrivals by 5981 foreign-flagged vessels in Australian ports (Australian Maritime Safety Authority, 2019). We note that there is an increasing trend of arrivals prior to 2019 which would likely increase the frequency of incursions over time. Adjustment may be required to the annual rate of incursions to reflect the increasing trend of arrivals.

Although vessel type is not required to implement the models recommended by Barry et al. (2015) and Atalah et al. (2022), average speed varies significantly with vessel types. In the case that average speed is not available, we will use vessel type as a proxy. We are aware that the data on time since the last AFC and time since the last out-of-water maintenance may not be available. If this is the case, we assume a uniform distribution on (0, 2190) for the time (days) since the last AFC.

Ideally, we should obtain the exact values of the risk predictors for all the arrivals and compute the relative risk for each vessel. For example, to utilise the estimated model from Barry et al. (2015), we should first obtain the information on the port of last call and the first arrival port for each vessel, and subsequently determine port types and search for water temperature and salinity at each port. However, this could be very time-consuming.

We simplify this task by grouping the arrivals in the following ways:

1) Group ports of the last call by ecoregion as used in Cope et al. (2015). Other region grouping criteria can also be applied if each region is not overly large such that there is a large variation in water temperature and salinity.
2) Group ports of arrival by ecoregion. We could also work with individual Australian ports since most international arrivals occur at a few larger ports.
3) Given that it is very time-consuming to identify the harbour type for every single port of origin and arrival, we make a simple assumption that the number of vessels in each category of port type change is equal.

2.5 Using summarised vessel data

In the case that only summarised vessel data are available, we can modify the calculation of absolute risk to accommodate this data type. Assume that we have two vessel risk variables, Factor 1 with levels of 1, 2, 3, and 4, and Factor 2 with levels of A, B, C, and D. The data format is shown in Table 8. There are in total 16 risk categories. We obtain the number of vessels in each risk category, represented by I_{ij} in Table E.8.

Table E.8. Summarised Vessel Data

Number of vessels		Factor 2			
		A	**B**	**C**	**D**
Factor 1	**1**	I_{1A}	I_{1B}	I_{1c}	I_{1D}
	2	I_{2A}	I_{2B}	I_{2C}	I_{2D}
	3	I_{3A}	I_{3B}	I_{3C}	I_{3D}
	4	I_{4A}	I_{4B}	I_{4C}	I_{4D}

For a risk category ij, we determine the relative risks of a vessel from this category, represented by rr_{ij} and construct Table 9. The absolute risk of a vessel from this category can be written as $rr_{ij}s_1$, where s_1 is the absolute risk of the reference vessel. Since the absolute risks of the vessels from all the risk categories add up to 1, we have $\sum_{i=1}^{4}\sum_{j=A}^{D} I_{ij}r_{ij}s_1 = 1$. Therefore, we obtain the following estimates of absolute risks:

$$s_1 = \frac{1}{\sum_{i=1}^{4}\sum_{j=A}^{D} N_{ij}r_{ij}} \text{ and } s_{ij} = \frac{r_{ij}}{\sum_{i=1}^{4}\sum_{j=A}^{D} N_{ij}r_{ij}}.$$

We can easily extend this approach to more risk factors which will lead to more risk categories.

Table E.9. Relative Risk for Each Category

Relative risk		Factor 2			
		A	**B**	**C**	**D**
Factor 1	**1**	rr_{1A}	rr_{1B}	rr_{1c}	rr_{1D}
	2	rr_{2A}	rr_{2B}	rr_{2C}	rr_{2D}
	3	rr_{3A}	rr_{3B}	rr_{3C}	rr_{3D}
	4	rr_{4A}	rr_{4B}	rr_{4C}	rr_{4D}

3 Ratemaking

3.1 Principles

In commercial insurance, insurance premiums must be sufficiently high to achieve the rate of return required by shareholders. Moreover, premiums must be sufficient to ensure that the insurer has an acceptably low insolvency probability and high credit rating. The price or premium that the insurer charges to policyholders is based on the sum of three components and can be expressed as follows:

$$\text{Premium} = \text{Expected loss} + \text{Risk Load} + \text{Expense Load},$$

where the expected loss caused by policyholders reflects the actuarial principle that the rate is based on risk. The expected loss is determined by the occurrence probability of an insured event and the incurred loss. The risk load is determined by the uncertainty surrounding the loss. The expense load covers administrative costs such as underwriting expenses, commissions, settlement expenses, and profits.

The risk load is an important component of the pricing equation. Standard deviation is often used as a measure of uncertainty. We assume that the risk load is set to a multiple of standard deviation. A higher risk load is applied when there is greater uncertainty associated with the annual loss. For risks that are difficult to quantify, the estimated annual loss suffers from great uncertainty, thereby leading to high insurance premiums. The risk load reflects the insurer's concern with the solvency constraint and the need for additional capital in case of extremely large claims.

3.2 Pricing biofouling risk insurance

For the biofouling insurance considered in this project, the expense load is assumed to cover the monitoring cost of biofouling risk only. We assume that there is no uncertainty in future monitoring costs and that the costs are equally shared by all the vessels coming to the port. Other costs can be easily added to the expense load if required. The insolvency risk of the insurance scheme is low since the insurance is backed by the government. However, we should still set a premium such that the probability of insufficient funds to pay for claims and expenses is below a certain threshold.

Let us denote the monitoring cost by MC. The cost attributed to individual vessels is $\frac{MC}{I}$. Following what we described in previous sections, the number of incursions caused by vessel i follows $\text{Poisson}(0.2s_i)$ while the response cost given an incursion follows a discrete distribution. Therefore, the annual loss caused by the ith vessel follows a compound Poisson distribution, the mean and expectation of which can be expressed as follows:

$$E(L_i) = 0.2s_iE(C),$$
$$Var(L_i) = 0.2s_i\left[\left(E(C)\right)^2 + Var(C)\right].$$

Assuming that the risk load is equal to λ times the standard deviation, the premium charged to the ith vessel is equal to

$$\pi_i = 0.2s_iE(C) + \lambda\sqrt{0.2s_i\left[\left(E(C)\right)^2 + Var(C)\right]} + \frac{MC}{I}.$$

3.3 Bonus-Malus system

When an incursion occurs, it may be possible to attribute the incursion to a small number of vessels. In such instances, these specific vessels will not be required to cover the response costs. Instead, the response costs will be paid from the collected insurance premiums. However, the tracing results can be used as a justification for raising the insurance premiums for these vessels. This is similar to the practice in motor vehicle insurance where claim experience is used to adjust premiums. This mechanism is referred to as the Bonus-Malus system.

Bonus: For each year that a vessel is not associated with an incursion, its premium may be reduced, often referred to as a “no claims discount” or “no claims bonus”. The purpose of such a scheme is to incentivise best practices to mitigate biofouling risks.

Malus: Conversely, if a vessel is identified as contributing to an incursion, its premium for the following year may be increased, which is the “malus” part of the system.

The objective of this system is to create financial incentives for policyholders to minimise biofouling risks and to increase premiums for those who pose higher risks. The specifics of how much the premium can change, and which incursions count towards the bonus or malus need to be clearly outlined in advance.

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Appendix F: Biofouling Insurance Pricing with Probabilistic Risk Analysis — Results.

Milestone 10 Report

Zhou, R., Li, R., & Pitt, D. (2025). *Biofouling insurance pricing with probabilistic risk analysis — results*. Unpublished Milestone 10 report, CEBRA 21C, Centre of Excellence for Biosecurity Risk Analysis, University of Melbourne.

[supplied as a stand-alone PDF]

Appendix G: Payoff matrix for vessel entry strategies

The payoff matrix (Table G.1) created to illustrate a biosecurity risk insurance market approach to biofouling management has been based on the following assumptions.

Biofouling mitigation effort - Biofouling mitigation interventions influence the biosecurity risk rating of inbound vessels. These interventions can take the form of structural features embodied in vessel design and construction and as anti-fouling treatment (AFC) of the hull or other vessel components. Whilst these interventions typically involve large lumpy costs, they need to be amortised over the life of the vessel, in the case of structural measures, and over the effective life of AFC treatments.

Biosecurity risk insurance premiums – Insurance premiums vary according to the risk rating of each vessel as set out in Table 2. These premiums include loss exposure arising from administering the biosecurity system, monitoring and surveillance costs, and costs incurred in responding to incursions of exotic pests and diseases as they arise. They do not include uninsurable risks.

Vessel inspection – Vesel inspection refers to a range of approaches that could be used to determine the biofouling risk status of vessels. These range from an audit of information about the type of vessel, AFC treatment and AFC vintage; through to underwater inspection of the vessel hull. The cost of vessel inspection and the quality of information about biosecurity risk will vary according to the type of vessel inspection required. A more complex biosecurity inspection regime than depicted in Figure 1, could include a progression of vessel inspection methods with more costly and accurate methods triggered by failure of less costly/accurate types of inspection. The true cost of providing vessel inspection is included in the payoff matrix.

Table G.I: Example payoff matrix for vessel entry pathways

VES (risk rating): **Cost item:**	**VDE^ (Unacceptable)**	**VES4 (High)**	**VES5 (High)**	**VES6 (High)**	**VES7 (Low)**	**VES8 (Low)**
Biofouling mitigation effort	$0	-$2,000	-$2,000	-$2,000	-$10,000	-$10,000
Biosecurity risk insurance premium	$0	-$4,113	-$4,113	-$4,113	-$1770	-$1770
Vessel inspection	-$20,000	-$20,000	$0	-$20,000	-$20,000	$0
Demurrage and delay	-$1,000,000	-$100,000	$0	-$100,000		$0
Fine for false signalling	-$120,000	$0	$0	-$120,000	$0	$0
TOTAL	**-$1,140,000**	**-$126,113**	**-$6,113**	**-$246,113**	**-$31,770**	**-11,770**

^VDE: Vessel denied entry

Demurrage and delay costs – Commercial shipping involves complex, time sensitive scheduling of vessels itineraries. Unexpected delays, such as would occur when a vessel is required to undergo underwater hull inspection, imposes costs arising from demurrage and schedule disruption. Where port slots are lost, these costs can be extremely high. These costs are known by vessel operators (private information), vary between vessel and are not known by the biosecurity authority. Vessels denied access are assigned an arbitrary, but large, financial penalty ($1,000,000) to reflect the cost of not unloading cargo at the destination port.

Fine for false signalling – The monetary value of fines for false signalling are set at the sum of vessel inspection plus demurrage and delay costs as explained in Section 3.1.4.