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REVIEW

A conceptual framework for measuring and improving the resilience of biosecurity systems

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Abstract

1. Resilient systems can absorb and recover from disturbances and adapt to changed conditions to maintain system functionality. Uncertainty about the meaning of resilience and the attributes it requires has limited the application of resilience thinking in biosecurity. However, considering increasing pressures from trade, travel and climate change, enhancing the resilience of biosecurity systems is likely to be critical to reduce the impacts of pests and diseases on economies, societies and environments.
2. Here we provide a pathway for resilience thinking into risk management. Based on a literature review we discuss its benefits, develop an operational definition of resilience for biosecurity systems and identify the fundamental attributes that support resilience.
3. We show that resilient biosecurity systems can anticipate disturbances, cope with low-probability high-impact events and adapt to new and changing circumstances. The status of biosecurity system resilience can be measured using evaluative rubrics, which give decision-makers an overall performance rating and insight into system weaknesses. General measures, objective functions and simulation approaches are potential avenues for quantifying biosecurity system resilience in practice.
4. *Policy implications*: Adopting resilience thinking into biosecurity risk management has the potential to reduce the damages caused by invading pests and diseases. If resilience thinking is used alongside traditional risk analysis, then regulators can more effectively address and prepare for the systemic consequences of high-impact incursions and outbreaks of pests and diseases, which are unpredictable, low-probability events. However, the design of resilience-enhancing measures should be guided by economic principles and consider the rate of return of these measures over time.

KEYWORDS
biosecurity, disturbance, evaluative rubrics, pests and diseases, rate of return, resilience thinking, risk management

1 | INTRODUCTION

Biological exchanges, the transfer of species (of plants and animals) and diseases along migration and trading routes, have long been part of human cultural history (Crosby, 2003). However, in the early 19th century the rate of biological exchanges increased dramatically due to technological innovations associated with the industrial revolution, leading to an increase of first records of alien species (i.e. the number of species establishing in a new environment outside of their native range; Hulme, 2021). The introduction of pests and diseases is strongly linked to human activity, especially the movement of goods and people (Hulme, 2015; Seebens et al., 2017). We can observe introductions via contaminants on traded commodities; stowaways in luggage, containers and goods; intentional release; escape of pet species or cultivated plants; natural dispersal by wind and water; and human infrastructure acting as corridors (e.g. Suez Canal, UK Channel tunnel; Hulme, 2015).

If introduced pests establish in the recipient environment, and spread widely (i.e. they become invasive; Blackburn et al., 2011), or if disease outbreaks occur, then they can significantly damage economic, environmental and social assets. For example, the establishment and spread of Red Imported Fire Ants in the US and Puerto Rico showcase the devastating consequences that invasive species can have. The total economic damage of this pest has been estimated to be more than USD 6 billion per year across various sectors (e.g. agriculture, golf courses, electric and communications; Lard et al., 2006). Similarly significant are the impacts on human health (e.g. in the worst case, fire ant stings can be fatal; Vinson, 2013) and biodiversity of native wildlife (e.g. fire ants can threaten egg-laying and ground-nesting vertebrate species; Allen et al., 2004). Over the past 60 years, invasive species have cost Australia close to AUD 400 billion (USD 273 billion) in economic losses (Bradshaw et al., 2021) and the potential economic impacts of the plant pathogen *Xylella fastidiosa* on olive oil production in Italy may reach up to EUR 5.2 billion (USD 5.5 billion) over 50 years under a worst-case scenario (Schneider et al., 2020).

To make matters worse, some types of pest invasions and disease outbreaks are likely to establish and spread more frequently in the future due to increasing pressures (Ristaino et al., 2021; Sikes et al., 2018). These pressures include (1) the direct effects of international trade and transport on biological invasions (e.g. increased trade and transport volumes increasing the probability of introduction of pests and diseases) and (2) the indirect effects that trade has on the introduction and spread of pests and diseases through *resource extraction* (e.g. resulting in fragmented habitat that is more vulnerable to invasion), *urbanisation* (e.g. creating hotspots for introduced species richness through import of commodities and unintentional introductions), *atmospheric pollution* through shipping (e.g. making ecosystems more nutrient rich through nitrogen deposition, favouring exotic pests and diseases) and *climate change* (Essl et al., 2020; e.g. increasing fundamental niches for pests and disease vectors; Hellmann et al., 2008; Hulme, 2021). Global warming, with its heterogeneous impacts across countries and national incomes, will cause substantial changes in trade patterns and, with it, changes in pest pathways from host to importing countries (Camac et al., 2023).

Biosecurity protects assets from the damages caused by pests and diseases. A biosecurity *system* is the collection of management activities that national agencies with asset protection responsibilities implement to reduce the biosecurity risk posed by pests and diseases. Biosecurity activities create a ‘protective dome’ around a country's assets (Figure 1), but incursions and outbreaks can still occur because the early biological invasion process is stochastic (i.e. the timing and location of pest invasions or disease outbreaks cannot be predicted; Lewis et al., 2016) and government-implemented risk controls are not 100% effective in mitigating risk.

Biosecurity risk controls cover an administrative *continuum*: (i) before pests and diseases arrive at the border (pre-border; e.g. import risk analysis and import permits), (ii) on arrival at the border (border; e.g. inspections of containers and luggage, treatments and diagnostics) and (iii) after they have crossed the border (post-border, also called domestic; e.g. targeted and general surveillance and emergency response). Biosecurity systems are inherently complex because of the many interactions between participants and components of the system, including interdependencies, feedback loops, human behaviour and the regulatory landscape (Table 1; Schneider & Arndt, 2020). Participants in national biosecurity systems include all levels of government (national, regional and local), plant and animal production industries, industry representatives, businesses, non-governmental organisations, research providers, community groups and the general public (Bland et al., 2024).

To keep biosecurity risk to an acceptably low level, government decision-makers seek to balance the risks of introducing pests and diseases along various import pathways (e.g. via containerised air or sea cargo, international travellers, international mail) with the economic return by applying traditional risk analysis methods (Stoneham et al., 2021). However, risk analysis methods have shortcomings when dealing with lack of data, uncertainty and unpredictability (Anderies et al., 2013; Park et al., 2013).

Here, we address our overarching objective, to discuss the merits of including resilience thinking into biosecurity risk management. The focus of our paper is on low-probability high-impact incursions or outbreaks of pests and diseases. We first discuss the current approach to biosecurity risk management and then outline the advantages of a more systemic approach to biosecurity. To facilitate integration of such an approach we introduce an operational definition of resilience in biosecurity systems, including terminology (Box 1), key resilience stages and system states and resilience-promoting attributes. We also present a semi-quantitative approach for measuring resilience and explore practical considerations for improving resilience in biosecurity systems.

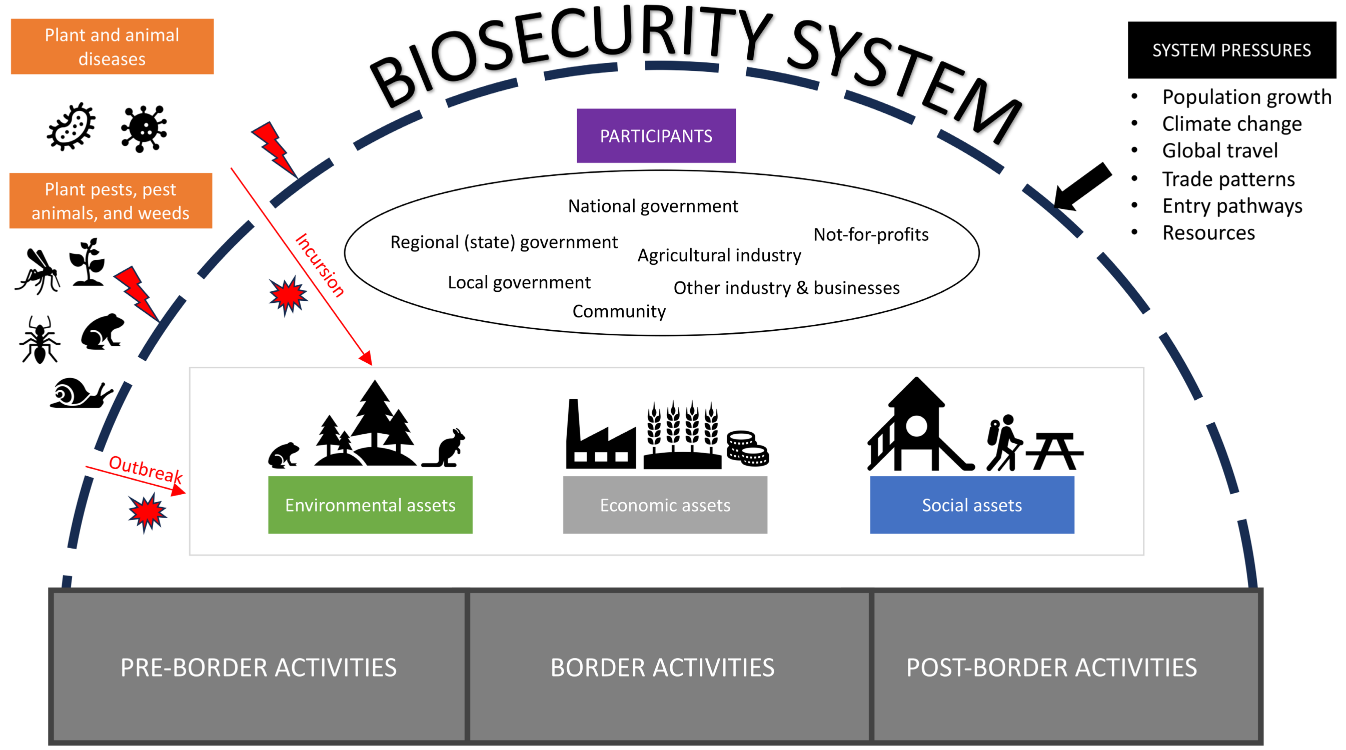


FIGURE 1 The elements of a national biosecurity system. Biosecurity activities that are implemented by a range of participants form a protective dome around environmental, economic and social assets. Pests, diseases and weeds can find gaps in this protection and enter, establish and spread in the landscape (incursions or outbreaks), potentially damaging these assets. External and internal system pressures influence the strength of the protection.

TABLE 1 Characteristic interactions within national biosecurity systems and their description, including relevant examples.

Interactions	Explanation
Interdependencies	Mutual dependencies between elements of the biosecurity system For example, government staff need to screen a proportion of containers and luggage to mitigate biosecurity risk, but effective border controls require sufficient government resources and capabilities
Feedback loops	Outputs or findings of biosecurity activities are used as inputs in other parts of the system For example, early detections of pest or diseases in the post-border environment should be communicated to border biosecurity risk managers to alert them to potential border breaches, and border personnel should inform agencies responsible for post-border risk management about observed trends in the frequency and type of detections
Human behaviour	The way in which participants in the biosecurity system interact with biosecurity issues and regulations For example, importers of goods who strictly comply with import conditions receiving a net benefit when border inspection rates are reduced based on their history of good compliance. Furthermore, compliant behaviour mitigates the risk of introducing biosecurity risk material (Stoneham et al., 2024)
Regulations	The suite of national and international rules designed to protect countries' assets from the damaging impacts of pests and diseases while not restricting international trade For example, the specific phytosanitary measures (e.g. fumigation, irradiation, cold and heat treatment) or packaging material exporting countries must adhere to as part of import conditions (Rossiter & Hester, 2024)

2 | BIOSECURITY RISK MANAGEMENT AND RESILIENCE THINKING

Invasive species and exotic diseases are significant issues for governments at all levels because the damages caused by pests and diseases are often systemic, which means that they can affect more than one type of asset. For example, the outbreak of foot and mouth disease (FMD) in the UK in 2007 had a significant impact on the livestock and food industries with losses of about GBP 3.1 billion in this sector, but it also affected cultural services, such as recreation, to a comparable level because fewer domestic and international tourists visited the infested areas (Thompson et al., 2002). Similarly, the invasion of Emerald Ash Borer (EAB) is causing both economic and environmental losses in the US; in managed community landscapes, affected urban ash trees need to be treated, removed and replaced, and researchers estimated these management costs, with no program to prevent further pest spread, to be USD 12.5 billion for the period from 2010 to 2020 (Kovacs et al., 2011). However, EAB

BOX 1 Glossary of terminology used in the context of biosecurity

Biosecurity system: The collection of management activities that protect a country's economy, environment and human population from the damaging impacts of pests and diseases.

Disturbance (*or sudden shock*): A low-probability disruption to biosecurity system performance by an incursion or outbreak with moderate to high consequences.

Performance: The ability of the biosecurity system to accomplish its intended objectives, to effectively protect economic, environmental and social assets from the negative impacts of pests and diseases.

Resilience: The system's ability to withstand the impacts of a disturbance, to respond to and recover from the impacts and to adapt to changed circumstances (Schneider & Arndt, 2020).

Resistance: The system's ability to deflect significant integrity losses following a disturbance by passively maintaining performance, or actively changing but retaining its identity (Grafton et al., 2019).

Recovery: The process of restoring the system's performance in response to a disturbance, aiming to achieve a stable state and level resembling normal operations.

Capacity and capability: Capacity is the appropriate quantity of financial, physical, human and organisational resources to support biosecurity systems. Capability is the appropriate quality of those resources (Schneider & Arndt, 2020).

induced ash tree mortality also leads to impacts on environmental assets. The decimation of ash trees in forest ecosystems changes understorey environments, nutrient cycles, amounts of woody debris, succession and ultimately forest community composition and ecosystem processes (Herms & McCullough, 2013). Furthermore, damages to economic and environmental assets often impact on people's livelihoods and well-being (Avelino et al., 2015).

Government risk analysts consider potential damages to assets by pests and diseases, albeit simplistically. They usually assess the biosecurity risk of import pathways introducing pests and diseases by quantifying risk in terms of likelihood and consequence, and mitigate residual risk until an acceptable level is achieved (ISO, 2018). This traditional approach to risk assessment and management performs relatively well for disturbances that are frequent enough and have low impacts (Davies, 2015; Park et al., 2013). However, incursions and outbreaks of pests and diseases are typically low-probability disturbance events of varying distinct consequences (i.e. sudden shocks), apart from plant incursions, which often have long lag phases in which the invading weed species exhibit non-linear increase in spread (e.g. on average 45.9 years for weed species established in Queensland; Osunkoya et al., 2021). High-impact disturbance events include the FMD outbreak in the UK in 2007, the outbreak of equine influenza in Australia in the same year, and the incursion of brown treesnake (*Boiga irregularis*) in the West Pacific Island of Guam in the mid-1940s (Garner et al., 2011; Rogers et al., 2017; Thompson et al., 2002). Because data for calculating probabilities are sparse, risks from low-probability high-impact events are likely to be underestimated by traditional risk analysis (Park et al., 2013; Taleb, 2007).

Moreover, contemporary risk analysis tends to operate in a reductionistic manner, applying linear processes that are designed to assess the likelihood and consequences of individual threats (Baum, 2015). In biosecurity import risk analysis, it is the risk of pests and diseases entering via a specific pathway, which is the combination of country of origin (e.g. Mexico), commodity (e.g. fresh lime fruit), and purpose (e.g. consumption). As a pre-border risk control measure, import risk analysis looks at potential threats in isolation and treats them as being independent of each other. In reality, multiple threats arrive on different pathways every year, as reflected in hundreds of annual notifications of intercepted pests and diseases (e.g. in Australia; Inspector-General of Biosecurity, 2019), with the potential to damage the same assets.

A focus on individual pathways lacks a holistic view of risk across the biosecurity continuum and misses important relationships and flow-on effects. Disregarding biosecurity system dynamics and applying a linear approach to managing risk likely underestimates overall risk, because incursions and outbreaks, and changes in risk profiles, affect other functions of the biosecurity system. For example, the outbreak of white spot disease in prawn aquaculture in south-east Queensland in 2016–17 resulted in a diversion of newly trained inspectors from ports around the country to meet inspection targets for prawn consignments, depleting other biosecurity operations of resources (Inspector-General of Biosecurity, 2017). An outbreak overseas can also have impacts on local biosecurity activities. In 2022, the outbreak of FMD in Bali prompted the Australian government to re-allocate some of its existing border resources towards inspecting the luggage of travellers arriving from Bali (DAFF, 2022). Similarly, adding countries to the list of seasonal target risk countries for Brown Marmorated Stink Bug in Australia requires additional treatments and verification steps (e.g. resource intensive unpack inspections) for goods imported from these countries (DAFF, 2023).

The resilience paradigm may offer a better framework for biosecurity management where traditional risk analysis falls short, because resilience thinking centres around the unpredictability of future disturbance events and the need for preparing for and minimising the consequences of system disturbance (Holling, 1973; Park et al., 2013). Resilience thinking emerged in materials science (Winson, 1932) and was first applied to ecology by Holling (1973), who described resilience as an ecological system's ability to persist under a disturbance and to absorb change to maintain functionality. Since then, definitions and interpretations of resilience have broadened to include the anticipation of potential threats, the timing and level of recovery, and long-term adaptation (Bruneau et al., 2003; Duchek, 2020). However, the resilience concept has had limited application in biosecurity management. This may be due to a lack of a cohesive definition of biosecurity systems and the attributes that could support system resilience, and how resilience could be measured and enhanced in practice (Duchek, 2020).

To re-iterate, significant biosecurity system disturbances (i.e. incursions or outbreaks) are low in probability, unpredictable and have flow-on effects to biosecurity activities elsewhere. Risk managers should acknowledge this uncertainty and the systemic nature of risk and adopt a more holistic approach to biosecurity risk management to better protect assets from damaging pests and diseases. In the context of socio-ecological systems, resilience describes the ability of these systems to absorb external pressure to change and persist, but also to maintain core structural and functional attributes (Holling, 1973). These desirable system qualities translate to biosecurity, where we talk about organisational resilience and thus the resilience of the biosecurity system. Enhancing biosecurity system resilience is a prevention measure that can be planned for. Strategic planning can alleviate the shortcomings of reactive management that does not have the operational capacity to respond effectively in an emergency. If a biosecurity system is resilient to disturbance, then it can absorb the impacts of a threat and maintain its performance under heightened stress, hence damages to assets can be avoided or lessened. Avoided damages include direct impacts, such as losses in market access, losses of environmental and ecosystem services, but also the costs of post-border biosecurity activities such as containment, eradication or long-term control of established pests and diseases (Stoeckl et al., 2023; Stoneham et al., 2021). Potential benefits of resilience-based risk management reach even further. If resilient biosecurity systems can minimise the number of invasive species entering, establishing and spreading, they can reduce the magnitude of the biodiversity conservation task.

3 | DEFINING RESILIENCE OF BIOSECURITY SYSTEMS

To facilitate integrating resilience thinking into biosecurity risk management we propose to conceptualise biosecurity system resilience broadly by considering system performance before, during and after a disturbance. This scope reflects advances in resilience thinking across disciplines and acknowledges that biosecurity activities such as intelligence gathering, resource allocation, strategic planning and organisational learning contribute to risk mitigation and overall system resilience.

Resilience is a relative system characteristic; a system can only be more or less resilient on a spectrum (ISO, 2017). Based on our literature review (Box 2), our schematic depiction of system response to a disturbance shows the various stages and associated attributes of resilience in biosecurity systems (Figure 2). We also include state transitions (Henry & Ramirez-Marquez, 2012) that biosecurity systems go through when they are affected by an incursion or outbreak. Resilience integrates over the system's ability to effectively respond to a disturbance (e.g. an incursion of a plant pest or disease) and can be measured by using system performance as a proxy.

BOX 2 Literature review on system resilience

We reviewed original research publications using Web of Science (1945–2019), Google Scholar and the grey literature. The search strings used were system resilience; resilience metrics; resilience evaluation; resilience quantification; organisational resilience; resilience AND robustness AND system. We also scanned references listed in meta-analyses of system resilience and/or robustness (e.g. Bhamra et al., 2011; Hosseini et al., 2016). We selected articles that, following abstract reviews, were deemed relevant for defining system resilience. In total, we identified 76 relevant references.

The amplitude of the response to a disturbance depends on the severity of the disturbance and the system's innate *resistance* (i.e. its ability to deflect significant integrity losses by maintaining performance or adjusting internal components; Grafton et al., 2019). The duration of performance *recovery* depends on the ability of the system to reorganise (Walker, 2020). At the extremes of the resilience spectrum, biosecurity systems are highly resilient to disturbances caused by incursions and outbreaks (i.e. high resistance to performance impacts with fast recovery; green line in Figure 2) or not sufficiently resilient (i.e. low resistance to performance impacts with slow recovery; blue line). The notion that systems, be they socio-ecological or biosecurity systems, can reach or cross so-called 'tipping points' may be problematic because these events are hard to measure (Pimm et al., 2019). Nevertheless, biosecurity system performance can be significantly reduced when multiple threats stretch available resources and thereby affect system effectiveness in protecting assets. For example, system performance can be reduced when some activities (e.g. export certification, border diagnostics and offshore surveillance) can no longer be undertaken to the required quality or timeliness because of the impacts of multiple outbreaks and the ensuing re-direction of limited resources.

We defined the main stages that biosecurity systems go through, before, during and after a disturbance, as *anticipate*, *cope* and *adapt* (Figure 2; Duchek, 2020). System performance within those stages is supported by the following five system attributes (derived from Rodin, 2014): *aware* and *prepared* for the anticipate stage, *resourced* and *responsive* for the cope stage and *adaptive* for the adapt stage. These system attributes apply across the whole biosecurity system to some extent, but some resilience stages rely more on some attributes than others.

3.1 | Anticipate

Before a disturbance, a biosecurity system is in a stable state and system performance oscillates around an average (e.g. determined by workforce or budget fluctuations). The level of performance that

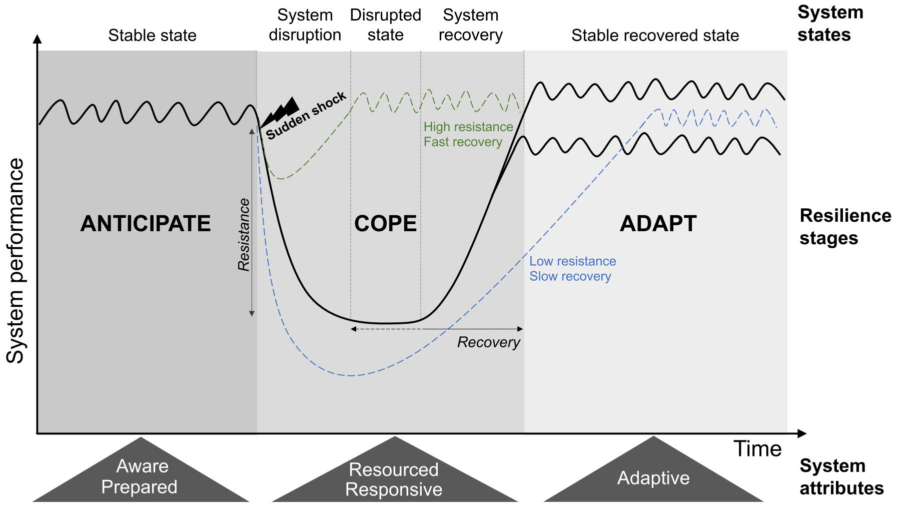


FIGURE 2 The effects of disturbance on the performance of biosecurity systems. The resilience process comprises three stages (i.e. anticipate, cope, adapt), each relating to supporting system attributes (i.e. aware, prepared, resourced, responsive and adaptive) and system states (as described in Henry & Ramirez-Marquez, 2012). Figure was adapted to biosecurity systems from Grafton et al. (2019).

constitutes prior system conditions is not necessarily obvious, depending on the time scale of observation and natural performance fluctuations (Pimm et al., 2019). Sudden shocks (i.e. incursions or outbreaks) trigger high-amplitude changes in performance as system resources are reorganised. Biosecurity systems require capabilities that allow system participants (e.g. government agencies, industries, citizens) to be *aware* of and *prepared* for sudden shocks. For instance, risk analysts undertake environmental scanning and gather intelligence that allow them to continuously identify, assess and prioritise current and emerging risks (Schneider & Arndt, 2020). To support biosecurity risk management during emergency situations, decision-makers implement specific preparedness provisions, including response agreements, biosecurity plans, training and simulation exercises, support tools (e.g. pest databases, resource tracking systems, disease spread models) and awareness-building and education activities (Schneider & Arndt, 2020).

3.2 | Cope

Following a sudden shock, reductions in performance vary with the level of resistance of the system (Henry & Ramirez-Marquez, 2012). While in a disrupted state, the system prepares for and initiates recovery and then recovers until a new stable state is reached (Najarian & Lim, 2019). To support the coping process, biosecurity systems need to be *resourced* and *responsive* (Schneider & Arndt, 2020). A biosecurity system that is well equipped with financial, physical and human resources is more likely to halt a reduction in system performance earlier and recover from it rapidly (Schneider & Arndt, 2020). Being responsive means that the biosecurity system can respond to a disturbance quickly, draw on sufficient resources and administer incident management in a coordinated and effective manner (Schneider & Arndt, 2020).

A common measure to improve resilience is to build functional redundancy in the workforce or physical resources (Gibson & Tarrant, 2010), so that, for instance, routine diagnostics services can still be delivered across the system even if a large proportion of diagnosticians have been directed to an emergency. Capacity (or quantity) alone is not sufficient; biosecurity systems also need the right kind and quality of infrastructure, skill sets and other organisational capabilities (e.g. strategic planning and governance) to support the coping process. Building and maintaining functional redundancy at times when the biosecurity system does not need to utilise extra staff or infrastructure appears wasteful, but this resilience measure pays off in an emergency. It is, therefore, crucial that risk managers resist the temptation to save resources by ignoring or eliminating functional redundancy.

3.3 | Adapt

When the biosecurity system has recovered to a new stable state, a learning process commences that includes further recovery from the disturbance and adaptation to new circumstances (Schneider & Arndt, 2020). Resilient systems change and reorganise internally to stay broadly similar in function, rather than bouncing back to their original state (Walker, 2020). Biosecurity systems are *adaptive* when decision-makers systematically review key aspects of biosecurity incidents and make relevant changes to business processes and policies (e.g. through organisational learning). For example, regulators may implement new risk management actions (e.g. establish domestic biosecurity zones or impose quarantine measures), adjust resource capacities and capabilities, update disease or pest spread models, or apply existing resources to long-term management programs (Schneider & Arndt, 2020). Monitoring and evaluation support this process by assessing critical aspects of system performance (Arndt, 2024; Gregory et al., 2012).

While our paper primarily focuses on low-probability, high-impact disturbance events (i.e. incursions or outbreaks of pests and diseases), we recognise an opportunity to explore the resilience of biosecurity systems to incursions of threats with a moderate probability and lower initial impacts; examples include plant incursions with substantial lag times. Species exhibiting a prolonged, non-linear increase in spread have effectively overcome entry and establishment obstacles but have not yet encountered favourable conditions for further expansion. Resilient biosecurity systems may anticipate 'slow-burn' disturbances by identifying taxonomic groups displaying this invasion pattern elsewhere and pinpointing factors that transform initially low-impact invaders into biosecurity threats, causing widespread damage. Responses to weeds that have reached a wide distribution before detection are usually driven by long-term management considerations rather than immediate coping mechanisms (i.e. control or eradication efforts). Learning from and adapting to this type of disturbance could involve translating insights from previous events into specific measures, such as updates to priority weed lists for system preparedness and designing community awareness campaigns for general surveillance.

4 | MEASURING THE RESILIENCE OF BIOSECURITY SYSTEMS

Measuring resilience at the three stages is challenging in practice because there are no off-the-shelf solutions. Resilience measures need to be context specific and based on well validated cause-and-effect relationships between interventions and resilience outcomes (Jones et al., 2021). System resilience can be measured using qualitative, semi-quantitative and quantitative approaches (Quinlan et al., 2016). Here, we focus on semi-quantitative and quantitative approaches.

4.1 | Semi-quantitative approaches

In general, semi-quantitative assessments involve individuals first making subjective judgements on resilience criteria or indicators based on scales and descriptors of qualitative attributes. These ratings are then synthesised using indices and scoring systems (e.g. Faulkner et al., 2018). In this paper, we present an innovative method for semi-quantitatively measuring system resilience using rubrics, which are measures constructed in tabular format—much like defined impact scales, which link discrete impacts to a numerical scale (Gregory et al., 2012). Rubrics consist of three elements organised in a table: performance standards, criteria for each resilience attribute and text descriptors of expected performance that pair criteria with standards (Martens, 2018).

We developed an evaluative rubric for the *aware* resilience attribute (Table 2; for example rubrics for the other resilience attributes see Appendix S1 in Supporting Information). In this example, the aware attribute is evaluated using five criteria pertaining to: environmental scanning, offshore surveillance, intelligence development and application, risk analysis coverage and risk prioritisation (Schneider & Arndt, 2020). Performance for each criterion is rated by individual assessors as either advanced (a score of 4), good (3), developing (2), inadequate (1) or evidence is insufficient to make an assessment (no score). Scores are then converted into proportions of the maximum score (i.e. a score of 1/4 is converted into a proportion of 0.25) and transformed using the arcsine function to prevent statistical errors when using skewed data (Fowler et al., 1998). Mean and confidence intervals are calculated, and results are back-transformed to restore data to its original scale. Weightings can be applied to criteria to acknowledge differences in relative importance. To synthesise rubrics, the mean proportion and confidence intervals are calculated for each criterion using the scores from all assessors and then calculated across all criteria.

To derive an overall performance rating for a resilience attribute, the mean proportion is compared to a grading system (Figure 3). Rubric results can be aggregated further to obtain a rating for each resilience stage or for overall system resilience. If jurisdictions in a country used the same rubric and method for synthesis, rubric results can also be used to compare system resilience at state level.

Rubrics enable valuation of program or system performance without input from specialist data analysts (King et al., 2013; Martens, 2018). The coordinators of an evaluation, whether they are government agencies or independent contractors, appoint multiple assessors who are experts and use the rubrics to make systematic and explicit judgements. These experts must have sufficient knowledge of business practices within the domains covered by the rubric. Ideally, assessors should also represent a diverse array of perspectives, encompassing different levels of government, industry, business (e.g. consulting), independent statutory bodies and researchers. Rubric outputs can be interpreted by a broad range of audiences, and underperforming areas are easily identified. For example, if a biosecurity system's awareness of current and emerging risks is poor, criteria ratings may reveal that environmental scanning and the use of its outputs are not adequate. To improve biosecurity system resilience, managers could then invest more resources in diversifying horizon scanning techniques or in improved analysis and prioritisation of scanning outputs (Wintle et al., 2020). Limitations of the use of rubrics are the time required for their setup (especially the initial phrasing of descriptors) and inconsistencies in interpretation by assessors. Semi-quantitative methods can describe the current resilience status of a biosecurity system (which can be re-assessed after management actions have been implemented, using previous results as a reference) but they cannot be used to model causal relationships among variables or to predict future resilience states.

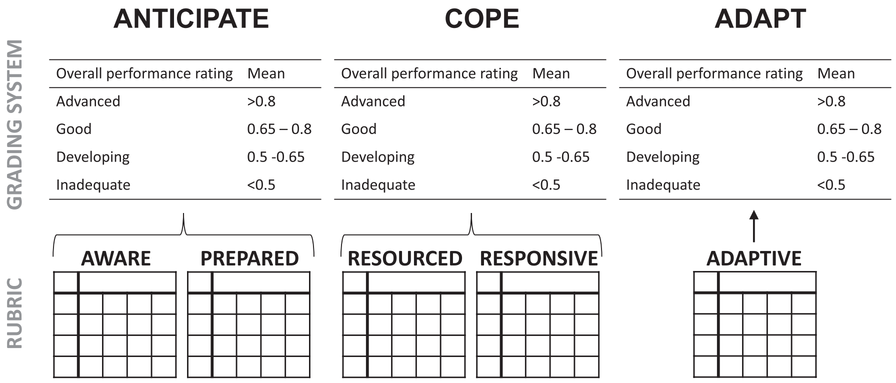
4.2 | Quantitative approaches

Quantitative approaches, and their use alongside semi-quantitative approaches, can provide a more nuanced picture of system resilience for decision-making. Hosseini et al. (2016) broadly categorised quantitative approaches for measuring system resilience into general measures and structural models. General measures quantify resilience by comparing system properties before and after disruption. Measures include system output, infrastructure quality, time to full recovery, economic loss or percentage of functionality lost (Hosseini et al., 2016). Structural models use system characteristics and behaviours to optimise system resilience by minimising total

TABLE 2 Evaluative rubric for the *aware* resilience attribute, derived for the Australian national biosecurity system. Generic descriptors were modified from Dickinson and Adams (2012) and specific descriptors were modified from Schneider and Arndt (2020).

	Performance standards[a]			
	Advanced (4)	**Good (3)**	**Developing (2)**	**Inadequate (1)**
Generic descriptors	Performance is very strong or exemplary	Performance is generally strong, with no significant gaps or weaknesses	Performance is inconsistent, with some gaps and weaknesses, and does not always meet minimum requirements	Performance is unacceptably weak and does not meet minimum requirements
Criteria for *aware* resilience attribute and specific descriptors				
Environmental scanning	Used systematically and rigorously across all risk areas (animal, plant and aquatic) and is based on best-practice techniques	Used systematically across most risk areas (animal, plant and aquatic), but there is less effective coverage in at least one area. Techniques employed are best practice	Used across at least one risk area and may use best-practice techniques	Undertaken on an ad hoc basis, does not cover all risk areas and does not use contemporary, best-practice techniques
Offshore surveillance design and techniques	Virtually always based on contemporary, best-practice survey design and statistical techniques. Undertaken by highly skilled personnel	Mostly based on contemporary, best-practice survey design and statistical techniques. Undertaken by skilled personnel	Some activities based on contemporary, best-practice survey design and statistical techniques. Undertaken by skilled personnel	Generally, not based on contemporary, best-practice survey design and statistical techniques. Not necessarily undertaken by skilled personnel
Development and application of intelligence	Information generated from all sources (scanning, networks, forums, surveillance and sentinel activities) virtually always successfully converted into valuable intelligence and applied to understanding, assessing and prioritising risk	Information generated from a range of sources mostly converted into useful intelligence and applied to understanding, assessing and prioritising risk	Information generated from a range of sources is sometimes converted into useful intelligence and applied to understanding, assessing and prioritising risk	Information generated from different sources is not systematically harnessed or converted into useful intelligence that can be applied to understanding, assessing and prioritising risk
Risk analysis coverage	Risk analyses provide excellent coverage of high-risk pests and diseases, import pathways, and commodities and provide very high levels of confidence that risks are managed appropriately	Risk analyses provide good coverage of high-risk pests and diseases, import pathways, and commodities and provide high levels of confidence that risks are managed appropriately	Risk analyses provide limited coverage of high-risk pests and diseases, import pathways, and commodities. Some gaps in coverage and timeliness of risk analyses limit confidence that risks are managed appropriately	Risk analyses provide poor coverage of high-risk pests and diseases, import pathways, and commodities. Significant gaps in coverage and timeliness of risk analyses, leaving little confidence that risks are managed appropriately
Risk prioritisation processes	Strong evidence that processes are in place to prioritise risk rigorously and transparently as a basis for resource allocation	Good evidence that processes are in place to prioritise risk rigorously and transparently as a basis for resource allocation	Limited evidence that processes are in place to prioritise risk rigorously and transparently as a basis for resource allocation	No evidence that processes are in place to prioritise risk rigorously and transparently as a basis for resource allocation

[a] The fifth performance standard, *Insufficient evidence* (i.e. evidence is unavailable or of insufficient quality to determine performance, no score), is not included in this table due to space constraints.



ANTICIPATE

Overall performance rating	Mean
Advanced	>0.8
Good	0.65 – 0.8
Developing	0.5 -0.65
Inadequate	<0.5

COPE

Overall performance rating	Mean
Advanced	>0.8
Good	0.65 – 0.8
Developing	0.5 -0.65
Inadequate	<0.5

ADAPT

Overall performance rating	Mean
Advanced	>0.8
Good	0.65 – 0.8
Developing	0.5 -0.65
Inadequate	<0.5

FIGURE 3 Synthesis of rubric results. The outcomes of the rubrics, the mean proportions, are compared to a grading system to derive overall performance ratings for the different resilience stages (anticipate, cope, adapt).

performance loss or recovery time or by simulating adverse scenarios (Hosseini et al., 2016).

The critical infrastructure and transport sectors provide useful examples of resilience quantification in practice. Faturechi et al. (2014) developed a stochastic optimisation model to maximise airport resilience, which was defined as the fraction of pre-disturbance arrival and departure volume that can be met post-disturbance given a maximum allowed repair time and total budget. Najarian and Lim (2019) proposed a metric for measuring the resilience of power generation using three factors and associated measures (in brackets): absorption (severity, as the number of inoperable generators), adaptation (generation capacity) and recovery (time to recovery). In summary, to quantify biosecurity system resilience, the use of appropriate general measures (e.g. time to full recovery of system performance) and objective functions (e.g. to optimise system performance given certain constraints), and the simulation of the effects of disturbances on system performance under different resilience-enhancing scenarios could all be suitable methodological choices.

5 | IMPROVING RESILIENCE IN BIOSECURITY SYSTEMS

Risk assessment and analysis are helpful in identifying the breadth of biosecurity threats, estimating their expected damages to assets and determining the level of risk based on likelihood and consequence (ISO, 2018). Resilience thinking, on the other hand, can prepare the biosecurity system to cope with unexpected events, uncertainty and potentially interacting threats (Park et al., 2013). While risk analysis is more focussed on anticipation, resilience thinking emphasises system-wide preparedness and ongoing adaptation to changed circumstances caused by incursions or outbreaks. Resilience thinking could work in tandem with risk analysis methods to harness the combined potential of these approaches for minimising the negative impacts of pests and diseases (Davies, 2015; Park et al., 2013).

Economic considerations are crucial when designing cost-effective preventative measures, as mitigating the fallout from sudden shocks by enhancing system resilience can be expensive and may not be worth the cost (Baum, 2015). Risk analysts need to know the costs and benefits of resilience-enhancing measures and their rate of return over time to prioritise resource allocation (Kompas et al., 2019). A focus on just benefit–cost ratios or cost effectiveness measures, as traditionally done may generate poor rankings or project evaluations. What we care about is the reduction in risk from an extra expenditure, or the extra benefit (in terms of extra avoided losses from a biosecurity event) compared to the extra costs of taking action. A quantitative approach to resilience estimation can allow decision-makers to evaluate the outcomes of different resilience-enhancing investment choices a priori, enabling the selection of rate of return adjusted cost-efficient measures from among a suite of proposed interventions.

Beyond incursions of pests and diseases, other factors can disrupt biosecurity systems, including budget cuts, expertise drain and ongoing long-term influences with long-term impacts on systems (press disturbances; Grafton et al., 2019) such as climate change, human health pandemics and changes in trade and tourism. These factors will need to be considered and incorporated into operational resilience frameworks for biosecurity systems. Failing to acknowledge the effects of continually rising pressures, particularly those of increased trade and travel, on the biosecurity system's capacity to protect from pests and diseases may undermine efforts to enhance the resilience of biosecurity systems. Especially if decision-makers neglect to appropriately enhance resources in response to the growing risk. Most importantly though, expanding the biosecurity system should be informed by a systems perspective on risk, coupled with investments grounded in economic principles and best decision-making practices.

Aside from the five system attributes in our definition, a resilient biosecurity system also needs overarching organisational characteristics that enable it to build and enhance resilience. Inclusive leadership, effective governance, a learning culture and strong social networks are all important characteristics of resilient organisations (Barasa et al., 2018). An organisational mindset that recognises the benefits of continuous learning can use disturbance events as opportunities to reflect on shortcomings and improve organisational capabilities that strengthen the resilience of biosecurity systems against future incursions and outbreaks (McManus et al., 2008). Where biosecurity agencies lack these characteristics, particularly a strong commitment to continuous improvement, resilience-improving activities should be supported by assessing and strengthening organisational characteristics.

When organisational characteristics adequately support resilience thinking, the operationalisation of the concept may commence by implementing the proposed evaluative rubrics designed to estimate the resilience of biosecurity systems. Evaluating the current resilience status of a national or jurisdictional biosecurity system encourages managers to adopt a holistic perspective on their operations, considering the various aspects that contribute to system resilience. The rubric results can identify weaknesses in the system, prompting further investigation and remediation. Enhancing biosecurity system resilience through a quantitative approach poses greater challenges. A detailed analysis of diverse past disturbance events (e.g. low-probability high-impact, moderate probability with initial low impact, etc.) can aid in identifying system parameters of interest for quantification. These parameters are known to be affected by the event and are recognised as influencing system resilience. Desktop reviews may examine published analyses or accounts of an event, but a more comprehensive understanding of event dynamics may require additional data collection. This can be achieved through semi-structured interviews, surveys or focus groups involving individuals with firsthand experience of the event's progression and impacts.

6 | CONCLUSIONS

Resilience thinking should be incorporated into government decision-making because it can complement current methods for managing risk which lack a systemic view of biosecurity risk. The resilience paradigm offers a framework for more effectively addressing the characteristics of incursions and outbreaks of pests and diseases – multiple, stochastic and low-probability events with potential high impacts. Systems thinking allows risk managers to better prepare the biosecurity system for more frequent disturbances and consequently avoid or lessen some of the damage to assets that ensues when pests and diseases establish and spread in the landscape. Our work has identified and described the resilience characteristics of biosecurity systems and presented a semi-quantitative method for measuring resilience. This lays a strong foundation for subsequent work on integrating resilience thinking into biosecurity risk management and decision-making. Ideally, these efforts would be embedded in an overarching framework for increasing biosecurity resilience that includes economic modelling so that resilience-enhancing measures cost-efficiently contribute to efforts to prevent the negative impacts of pests and diseases on economies, societies and environments.

AUTHOR CONTRIBUTIONS

Edith Arndt and Karen Schneider conceived the ideas and designed the conceptual framework; Andrew Robinson and Tom Kompas revised the article critically; Anaïs Gibert conducted the literature review; Edith Arndt and Lucie Bland led the writing of the manuscript; James Camac developed the rubric synthesis method. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Examples of evaluative rubrics for the resilience attributes of prepared, resourced, responsive, and adaptive.

Table S1. Evaluative rubric for the *prepared* resilience attribute, derived for the Australian national biosecurity system.

Table S2. Evaluative rubric for the *resourced* resilience attribute, derived for the Australian national biosecurity system.

Table S3. Evaluative rubric for the *responsive* resilience attribute, derived for the Australian national biosecurity system.

Table S4. Evaluative rubric for the *adaptive* resilience attribute, derived for the Australian national biosecurity system.

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