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The Boundary of the Market for Biosecurity Risk

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Imported goods create value in destination countries but also create biosecurity risk. Although widely used in other domains of the economy, risk markets have not been created to manage losses that occur when exotic pests and diseases are introduced with traded goods. In this article we show that not all biosecurity risks are insurable. Losses arising from effort needed to detect and respond to exotic pests and diseases that breach national borders appear to be insurable because *entry* of these threats and consequent response costs, can be regarded as random events. As pests and diseases *establish* and *spread*, however, loss of access to export markets and productivity losses display systematic risk and appear to be uninsurable. Other insurability criteria support this definition of the boundary of biosecurity risk markets. We use the Australian biosecurity system as an example, although the framework described in this study will be applicable to biosecurity systems worldwide. We argue that biosecurity risk insurance could be incorporated into the current biosecurity system but would require legislation mandating importers to purchase insurance. Advantages of actuarial pricing of biosecurity risk are: (i) an increase in economic efficiency to the extent that importers respond to the price of biosecurity risk; (ii) financial sustainability would improve because actuarial pricing creates a structural link between funds available for biosecurity activities and risk exposure; and (iii) equity issues evident in the current biosecurity system could be addressed because risk creators (importers) would fund response activities through the purchase of insurance.

KEY WORDS: Actuarial pricing; biosecurity risk; insurance

1. INTRODUCTION

Governments across the globe regulate imports and invest in other biosecurity activities to reduce the risk of introducing exotic pests and diseases through imported goods. It is, however, neither practical nor feasible to eliminate all biosecurity risks. To do so, imports and travel would need to be significantly reduced, onerous biosecurity interventions would be required and other natural vectors for pests and diseases would somehow need to be controlled. These interventions would be costly, increase the price of imported goods, and potentially lead to reciprocal trade sanctions.

Under the World Trade Organisation (WTO) the concept of an "appropriate level of protection" (ALOP) is used to define the compromise between the benefits of biosecurity interventions including human health, environmental or productivity benefits, and their impact on international trade. Biosecurity agencies typically implement ALOP via a range of interventions including: regulations that prohibit entry of high-risk goods; prescribed inspection and

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treatment of imports; offshore and border surveillance; partnerships with other national biosecurity agencies; scientific analysis and intelligence activities; and by maintaining a capacity to respond to incursions.

Decisions about the total investment in biosecurity effort and the distribution of resources across activities needed to achieve ALOP are typically made by a biosecurity agency via a centralized process which is informed by physical and financial assessments of biosecurity risk. In this article we examine the role for decentralized mechanisms in border protection. We focus on the biosecurity risks that imported goods impose on the domestic economy and the role that risk markets might play in the biosecurity system. We use the Australian biosecurity system as an example, although the framework described in this study will be applicable to biosecurity systems worldwide.

Following a brief overview of Australia's biosecurity system in Section 2, we provide an economic framing of biosecurity as it applies to border protection and summarize the principles relevant to efficient pricing of biosecurity risk. Section 4 defines the boundary of biosecurity risk markets based on an assessment of the insurability of biosecurity risks. The final section of the paper provides an outline of the institutions that would be needed to incorporate biosecurity risk insurance into Australia's national biosecurity system. This article represents the first phase of a larger research agenda. Subsequent research is proposed to apply actuarial pricing principles to selected imported goods and to estimate the economic efficiency gains from biosecurity risk insurance.

2. THE AUSTRALIAN BIOSECURITY SYSTEM

Australia is free of many major diseases and pests that have potential to negatively impact the economy, the environment, and in some cases human health. Biosecurity risks are managed through interventions including preborder control activities and border protection intended to reduce entry of exotic pests and diseases; and postborder controls to prevent and where possible eliminate exotic pests and diseases from spreading and establishing in Australia. In 2019–2020, the Australian Government made approximately $850 million in funding available for biosecurity programs and activities (Commonwealth of Australia, 2019). The institutions developed to manage biosecurity activities reflect international trade obligations and the distribution of powers and responsibilities between the states, territories and the Commonwealth as set out in the Australian constitution.

2.1. International Obligations

Under the WTO Agreement on the Application of Sanitary and Phytosanitary Measures (the SPS Agreement), signatory countries are entitled to set an ALOP to protect their natural environment, human health, and economic welfare. Biosecurity measures must, however, be science-based, transparent, and applied consistently to minimize the welfare-reducing impact on international trade. Australia's ALOP is articulated in the *Biosecurity Act 2015* (Cwlth), Section 5, as: *a high level of sanitary and phytosanitary protection aimed at reducing biosecurity risks to a very low level, but not to zero*. Australia implements this objective by considering biosecurity risks and economic returns. Biosecurity risk is measured in terms of the approach rate[1] of organisms of concern and the likelihood that these organisms will establish and spread and cause impact. Advice on investments in activities to manage biosecurity risks is provided by the risk return resource allocation (RRRA) model[2] (Craik, Palmer, & Sheldrake, 2017). Economic models are used to estimate the potential returns from biosecurity interventions for different pests and diseases (see, Section 4.2).

The Beale review of Australia's biosecurity system (Beale, Fairbrother, Inglish, & Trebeck, 2008) noted the operational difficulties created by the ALOP objective. It advocated transition towards a risk-based approach in which inspection resources and risk mitigation effort is allocated according to the risks that imports pose to Australia's ALOP (Rossiter, Hester, Aston, Sibley, & Woodhams, 2016). Australia subsequently adopted a risk-based approach to managing biosecurity risk, which involves a wide suite of arrangements and actions, refined through subsequent reviews into aspects of the biosecurity system (Craik et al., 2017; DAWR, 2015; Matthews, 2011; Schneider, Fraser, Dodd, Robinson, & Arndt, 2018).

[1] An estimate of the likelihood of entry of pests and diseases determined through inspection results.

[2] Postborder investments by the states and territories are not included in the RRRA analysis.

2.2. Constitutional Responsibility

Within Australia, the level and distribution of biosecurity effort between levels of government and other stakeholders is formalized in the Intergovernmental Agreement on Biosecurity (IGAB) (see, Beale et al., 2008; DAWR, 2015; Nairn, Allen, Inglis, & Tanner, 1996). Under this agreement, the Commonwealth, via the Department of Agriculture, Water and the Environment (the department), is primarily responsible for national preborder and border biosecurity activities (including external territories) and the states and territories are responsible for state borders and postborder activities. The department implements its responsibilities through: direct investments in biosecurity activities, international partnerships, research and surveillance to reduce Australia's exposure to biosecurity risks; and regulations that may require imports to undergo inspections and/or treatment and prohibits imports of others that pose unacceptable biosecurity risks.

The IGAB also defines the distribution of biosecurity responsibilities between the Commonwealth, states, territories and nongovernment parties (such as primary producers) for postborder biosecurity responses. The Emergency Plant Pest Response Deed (EPPRD) and the Emergency Animal Disease Response Agreement (EADRA) specify cost sharing arrangements between governments and industry where incursions of plant pests and animal diseases of national significance occur. A beneficiary-pays approach is broadly applied to signatories based on an assessment of the potential impact of biosecurity threats on public health, regional and national economies, trade and market access, and response or production costs[3]. For plant threats, Table I shows funding of emergency response activities varies from 100% public funding, where there is predominately public impact, to 20% government funding where impacts are assessed to largely accrue to privately owned businesses. Signatories to the EPPRD are required to establish mechanisms (i.e., levies on industry) to raise funds needed to implement emergency response plans. These levies are typically set at zero until an emergency arises and are applied until the agreed shares are refunded to government (Craik et al., 2017). An example of a recent response under the EPPRD is given in Box 1.

[3]Biosecurity threats to the environment or amenity values are considered under the National Environmental Biosecurity Response Agreement (NEBRA), which is an agreement between governments and has no industry parties.

Table I. Categorization of Emergency Plant Pests and Associated Ratio of Public: Industry Funding. Source: PHA (n.d.)

Category	Funding	Examples
Category 1	100% Government	Sudden oak death
Category 2	80% Government: 20% Industry	Khapra beetle
Category 3	50% Government: 50% Industry	Banana freckle
Category 4	20% Government: 80% Industry	Variegated cutworm

The agreement for emergency animal biosecurity incursions (EADRA), developed in a similar way to the plant deed, covers 66 animal diseases. Disease-specific response strategies are detailed in the Australian Veterinary Emergency Plan (AUSVETPLAN). Responses to aquatic emergency animal diseases will be funded under an industry–government aquatic emergency animal disease response agreement, currently under development. The aquatic agreement will cover emergency disease outbreaks affecting aquatic animals and the industries that rely on them. An example of industry and government funding of a response to an aquatic animal disease is given in Box 1.

A review of the IGAB (Craik et al., 2017) noted that the success of Australia's biosecurity system depends on all governments meeting their commitments, but concerns are emerging about the ability of some state and territory governments to meet these commitments due to funding pressures, growing volumes of inward passengers and sea cargo, and increasing diversity of traded goods. Suggested solutions to these pressures include: the inclusion of risk creators (importers) in emergency response agreements so that they contribute to the cost of controlling pest and disease incursions (COAG, 2012); and a levy on cargo imported to Australia by sea (Craik et al., 2017).

Box 1. Examples of Australian industry–government funding of disease management responses

1. Banana Freckle

Banana Freckle (*Phyllosticta cavendishii*), a serious fungal disease of Cavendish bananas, was detected in the Northern Territory, Australia, during 2013. A program to eradicate the disease commenced in 2014. The program was funded according to the EPPRD, with half of the cost met by industry and half by government. Industry's share of the eradication program amounted to $12m and was repaid to the Australian government between 2015 and 2019 through a compulsory banana-production levy. Eradication was achieved in early 2019.

2. White Spot Disease in prawns

In November 2016 an outbreak of the previously exotic white spot disease (WSD) was confirmed in south-east Queensland, Australia. An eradication program subsequently commenced and involved the destocking affected prawn farms, restrictions on fishing and movement of uncooked prawns and other crustaceans; and a six-month suspension of imports of uncooked prawns. Trade was suspended because infected imported prawns used as bait or berley were found to be the most likely cause of the outbreak (IGB, 2017; Knibb, Le, Katouli, Bar, & Lloyd, 2018). Eradication has not yet been confirmed.

The Australian government has provided a $20m assistance package for prawn farmers affected by WSD. The financial assistance was used to pay owner reimbursement costs for the initial response to the WSD outbreak, including destroyed stock, and the costs for a missed season of production. The industry contribution to the package is $4m and will be repaid over 10 years through the recently introduced a WSD repayment levy.

In summary, Australian governments and industry invest significant resources to reduce the risk that biosecurity threats enter Australia, and to respond to plant, animal, environmental, and social amenity threats that breach the national border. The allocation of biosecurity effort to border protection is determined by centralized processes that implement an ALOP based on consideration of physical biosecurity threats and the economic impact of these threats. Regulations on traded goods are the principal mechanism used to implement ALOP. Commonwealth powers are used to prohibit some high risk/high impact goods and to enforce testing and treatment protocols on other goods to reduce biosecurity risks. Where pests and diseases do enter, emergency response arrangements have been developed with the aim of eradicating the pest or disease. Funding of these activities is based on beneficiaries-pays principles in which levies are collected from affected industries to recoup an agreed proportion of the total expenditure initially incurred by government.

3. ECONOMIC FRAMING OF BIOSECURITY RISK

Biosecurity threats introduce risk into the Australian economy. Each inbound movement of goods carries some probability of introducing a pest or disease with some subsequent probability of causing economic, human health, and/or environmental loss. Three types of loss occur: (i) *response* loss, where entry of a biosecurity threat triggers effort needed to detect, control, and eradicate (where feasible) the threat; (ii) *productivity* loss, where a pest or disease reduces economic and/or environmental outputs produced from inputs; and (iii) *market access* loss, where a pest or disease causes loss of access to markets. These costs are not taken into account by importers but are imposed on other sectors of the economy as a *negative biosecurity risk externality*. This externality leads to missing markets for insurance that would otherwise protect importers against claims for financial losses caused from introduced pests and diseases. In the absence of intervention, this form of market failure can be expected to result in underinvestment in biosecurity effort by importers and selection of the "wrong" set of imported goods.

While this externality and consequent missing market problem establishes the case for government intervention in markets for imported goods, the mechanism used to correct market inefficiency must address important information and incentive alignment problems before an efficient level and type of biosecurity effort can be identified. In decentralized environments, information is unevenly distributed across the actors who make decisions. If unresolved, information asymmetry leads to decisions that do not utilize resources efficiently (see, Akerlof, 1970). In the biosecurity context, information needed to select the optimal set of imported goods and biosecurity effort is asymmetrically distributed between importers, governments, and other impacted businesses. Importers hold information about the profit margins that can be earned from importing goods; the biosecurity agency holds information about the consequences of different biosecurity threats, the impact of testing and treatment regimes, the costs of pest and disease response programs and so on; and other businesses, such as primary producers, hold information about the financial consequences of biosecurity threats. Some of this information is proprietary and hidden from other decisionmakers, some is costly to gather (e.g., where specialized modeling techniques are needed); but all relevant information must be revealed (truthfully) before resources can be used efficiently.

A related problem identified by Hurwicz (1972) is that dispersion of private information among economic agents can create incentive problems, referred to as incentive-compatibility. Incentive compatibility problems arise in decentralized economic systems where tasks are delegated to agents whose incentives do not align with those of the principal. The motivation of the subcontractors, for example, is to minimize costs—not to achieve the quality required by the final consumer of the service. This problem is typically addressed by introducing incentive structures into supply contracts that align the actions of the agent with the objectives of the principal (see, Laffont & Martimort, 2002). Kimura and Antón (2011) note that incentive compatibility is a problem in the biosecurity context because import decisions are delegated to profit-motivated importers who do not consider the national welfare implications of their decisions.

3.1. Efficient Pricing of Biosecurity Risk

Hurwicz and Reiter (2006) show that in decentralized environments, resources can only be allocated efficiently if the mechanisms employed cause truthful revelation of information, align the incentives of the various actors and adequately reward participation[4]. These mechanism design principles suggest that the centralized biosecurity systems employed in Australia and other countries cannot be expected to allocate resources efficiently primarily because they do not reveal all relevant information needed. Regulated biosecurity interventions, for example, suffer from the information asymmetry problem outlined by Laffont and Tirole (1993) and can be expected to lead to selection of the "wrong" set of imports and will not lead to the optimal selection of biosecurity interventions.

In decentralized economic systems, efficient allocation of resources can only be achieved through decentralized mechanisms such as markets. Risk markets are one class of decentralized, information-efficient mechanism that reveal efficient prices for risk and create incentives for risk takers to modify their behavior. Risk is priced efficiently when two conflicting influences are optimized. A portion of risk, referred to as unsystematic risk, can be reduced by redistributing risk from small to large organizations or collectives. This is referred to as risk pooling leading to a reduction in the cost of risk bearing. However, these benefits are dissipated because risk pooling reduces incentives for agents (performing delegated tasks) to produce the outcomes intended and this causes costs to rise. Laffont and Martimort (2002) explain that risk is priced efficiently when the marginal benefits of risk pooling equate with the marginal cost arising from the incentive effect. The following sections briefly explain these principles.

3.1.1. Risk Pooling

Risk pooling refers to the process by which some risk (referred to as unsystematic risk) can be reduced and under certain circumstances removed, through diversification. In an investment context, the capital asset pricing model (CAPM) defines how a diversified portfolio of investments can reduce overall risk.[5] The same principles apply to insurance where the total claim cost Y can be represented as:

$$Y = \sum_{i=1}^{n} X_i, \tag{1}$$

where n represents the number of exposure units over the period and X_i represents the loss resulting from the i-th exposure unit. To demonstrate the effect of pooling, we assume the variance of X_i is a constant σ^2 and the correlation coefficient between X_i and X_j for $i \neq j$ is also a constant $\rho \in [-1, 1]$. In Section 4.2, we argue that $0 \leq \rho < 1$ in the context of biosecurity risk; specifically, ρ is expected to be close to 0 for response losses but close to 1 for productivity and market access losses. Given the assumptions made, we have

$$Var[Y] = Var\left[\sum_{i=1}^{n} X_i\right] = n\sigma^2 + 2 \times \frac{n(n-1)}{2}\rho\,\sigma^2$$
$$= n\sigma^2 + n(n-1)\rho\sigma^2. \tag{2}$$

[4]Other requirements for an efficient mechanism are described in Hurwicz and Reiter (2006).

[5]The CAPM and its associated mean–variance framework suggest that the variance of a portfolio's returns can be made lower than that of the constituent securities' returns and can be minimized by appropriately mixing the constituent securities. As demonstrated in Equation (3), analogous results can be obtained for a portfolio of biosecurity risk insurance contracts.

As a result, the variance of the average claim per exposure unit is:

$$Var\left[\frac{1}{n}\sum_{i=1}^{n}X_i\right]=\frac{1}{n^2}\ \left(n\sigma^2+n\left(n-1\right)\rho\sigma^2\right)$$
$$=\frac{\sigma^2}{n}+\frac{n-1}{n}\rho\sigma^2. \qquad (3)$$

The implications of this expression are twofold. First, when correlations are not perfectly positive (i.e., $\rho < 1$), the variance of the average claim would be strictly smaller than that of the variance of each individual claim, as

$$\frac{\sigma^2}{n}+\frac{n-1}{n}\rho\sigma^2<\frac{\sigma^2}{n}+\frac{n-1}{n}\sigma^2=\sigma^2 .$$

In a biosecurity context, this result suggests that the biosecurity risk created by individual consignments of imported goods when pooled across all consignments ($\frac{\sigma^2}{n}+\frac{n-1}{n}\rho\sigma^2$) will be smaller than the variance (σ^2) faced by an individual importer. Second, when n becomes very large, the variance of the average claim approaches $\rho\sigma^2$, a constant that is independent of n. This result suggests that biosecurity risk cannot be eliminated completely because of the residual systematic risk ($\rho\sigma^2$) which arises from the nonzero correlation ρ between exposure units.

3.1.2. Actuarial Pricing of Risk

Actuarial pricing of risk links the insurance price (premium) with the riskiness of the activity. This process ensures the price of risk is sufficient to cover expected claims (and expenses) and improves incentive compatibility by introducing risk-based premiums. The first step in applying actuarial pricing principles to biosecurity risk is to develop an aggregate loss model:

$$L\ (t)=\sum_{i=1}^{n}\sum_{j=1}^{N_i(t)}Y_{i,j}\ (t)\ . \qquad (4)$$

In this model, adapted from nonlife insurance, $L(t)$ represents the aggregate loss over an exposure period t, $N_i(t)$ denotes the random number of losses arising from the ith exposure unit over an exposure period t, and $Y_{i,j}(t)$ is the random dollar amount of the jth loss arising from the ith exposure unit over an exposure period t. Given that biosecurity risk-related claims arising from pest or disease incursions can be expected to be "low-frequency-high-severity," it is anticipated that $N_i(t)$ can be framed as a counting distribution such as Poisson, whereas $Y_{i,j}(t)$ can be represented by a "heavy-tail" continuous distribution such as a Pareto distribution. Estimates of the random number of losses $N_i(t)$ would need to be derived from historical loss frequency data, which appear to be available from existing information systems developed by the department. Information about the distribution of losses ($Y_{i,j}(t)$) from biosecurity incursions is also needed and appears to be available from epidemiology models, such as the Australian animal disease spread (AADIS) hybrid model, at least for selected biosecurity threats. The AADIS model is a deterministic equation-based model that represents within-herd spread, and a stochastic, spatially explicit agent-based model for between-herd spread (see, Bradhurst, Roche, East, Kwan, & Garner, 2015). It provides estimates of losses arising from mitigation costs, domestic movement restrictions as specified in disease-specific response strategies and includes estimates of the cost of trade sanctions. This methodology could be applied to other pests and disease incursions if required.

Base biosecurity insurance premiums for different classes of imports and origins of imports would be determined by averaging the estimate of the expected aggregate loss ($L(t)$ in Equation 4) over the total number of exposure units. Depending on the nature of the import, the exposure unit can be defined as, for example, a collection of homogeneous import consignments. It should be noted that the base premium would not solely reflect the level of biosecurity risk that is specific to a particular import but could be adjusted to reduce adverse selection problems. Adjustments could be based on a collection of rating variables such as those used for various types of nonlife insurances as shown in Table II. In

Table II. Examples of Rating Variables for Various Types of Nonlife Insurances

Type of Insurance	Rating Variables
Personal automobile	Driver age and gender, model, year, accident history
Homeowners	Amount of insurance, age of home, construction type
Workers compensation	Occupation class code
Commercial general liability	Classification, Territory, limit of liability
Medical malpractice	Specialty, Territory, limit of liability
Commercial automobile	Driver class, Territory, limit of liability

the biosecurity context, factors such as the type of good, origin of good, type of processing, and certification could be considered in applying actuarial pricing principles to biosecurity risk. The biosecurity risk insurance premium for an import would be calculated as the product of the base premium and a multiplier that reflects the values of the import's rating variables. In practice, such multipliers can be determined using a simple univariate classification approach, in which the rating variables are considered one at a time. However, more sophisticated multivariate approaches relying on "big data" analytic methods such as generalized linear models, cluster analysis, and neural networks may be possible depending on the sophistication of Australia's epidemiology modeling capabilities and biosecurity data systems.

3.2. Economic Assessment of the Current Biosecurity System

Australia's biosecurity system relies on centralized decision and resource allocation processes. This approach does not price biosecurity risk efficiently. Whilst some level of risk pooling is achieved in the current system because government bears a significant share of biosecurity risk, this approach will not minimize unsystematic risk because importers and other nongovernment agencies are excluded from risk pooling opportunities. Similarly, the current system does not distribute risk according to actuarial principles. Instead, it applies a beneficiaries-pays principle (implemented through the EPPRD, EADRA, and forthcoming aquatic deed) to distribute risk and in doing so, foregoes any beneficial behavioral responses that might be achieved from exposing importers to the cost of biosecurity risk. It also means that importers do not contribute financially to exotic pest and disease response efforts even though they contribute to the creation of these risks. The extent to which these information, incentive, and funding problems can be resolved depends on whether decentralized mechanisms, in this case biosecurity risk markets, can be designed, created, and implemented. The boundary of risk markets is explored in more detail in the following sections by firstly assessing the insurability of different types of losses caused by exotic pests and diseases incursions.

4. THE INSURABILITY OF BIOSECURITY RISK

Risk markets are already used to manage biosecurity risks relevant to specific commodities such as potatoes in the Netherlands[6] and citrus fruit in Israel[7], but have not been incorporated into national biosecurity systems. Several studies have discussed potential biosecurity applications of insurance more broadly (see, Martin, 2006; McNeely, Mooney, Neville, Schei, & Waage, 2001; Shine, Williams, & Burhenne-Guilmin, 2005; and Baroni, 2013); but Perrings, Williamson, and Dalmazzone (2000) and the U.S. National Plant Board (1999) appear to have been the first to suggest an insurance approach to biosecurity in which government and groups of importers share an insurance pool to cover liabilities that arise from the introduction of biosecurity threats. Martin (2006) suggested multiple improvements to the management of invasive risks including insurance as "a more sophisticated approach to incident control" and considered the case for compulsory participation. Anderson, McRae, and Wilson (2012) proposed a mechanism in which importers would be required to take out personal insurance to cover the country losses incurred in the event of disease and pest incursions and Craik et al. (2017) proposed a similar insurance model, operated by the Australian Government. Baroni (2013) analyzed liability insurance more closely, proposing that insurance include classification for different biosecurity risks.

A number of countries including Australia, New Zealand, and Denmark have introduced, or are considering an informal insurance mechanism implemented as a levy on primary producers and/or imported goods as a means of funding biosecurity activities. These schemes are typically motivated by financial considerations, but the economic efficiency advantages of an insurance approach to biosecurity risks may also be substantial, provided these risks are insurable and it is technically feasible to calculate insurance premiums. The insurability of biosecurity risks is assessed in the following sections by applying the criteria developed by Berliner (1982) and Hart, Buchanan, and Howe (1996) (HBH). The criteria are listed in Tables III and IV.

4.1. Societal Insurability Criteria

We consider Berliner's *Societal* insurability criteria first because government intervention will be needed to address the negative biosecurity risk externality identified in Section 3. In the Australian context, Commonwealth legislation would be needed to

[6]http://www.potatopol.nl
[7]http://www.jaffa.co.il

Table III. Berliner Insurability Criteria Assessed Against Biosecurity Risk

Category	Description	Response Losses	Productivity Losses	Market Access Losses
Actuarial	(1) *Randomness of loss occurrence*—loss exposures independent	Response loss occurrence determined by random entry of biosecurity threats in imports.	Nonrandomness introduced where threats are highly transmissible and mitigated by the availability and effectiveness of response measures.	Market access loss exposure is not an independent event.
	(2) Predictability of loss occurrence—must be predictable	Response losses are predictable.	Moderately predictable.	Difficult to predict.
	(3) *Maximum possible loss*—must be manageable	Maximum losses manageable.	Maximum losses moderate.	Maximum losses very large.
	(4) Average loss per event—must be moderate	Average losses moderate.	Average losses moderate to large.	Average losses large.
	(5) *Loss exposure*—must be large	Loss exposure large relative to the profits made from importing goods.	As per response loss assessment.	As per response loss assessment.
	(6) *Information asymmetry* - Adverse selection manageable - Moral hazard not excessive	Similar to other insurable risks. No incentive for importers to trigger payouts.	Similar to other insurable risks. As per response loss assessment.	Similar to other insurable risks. As per response loss assessment.
Market	(7) *Insurance premium*—costs recoverable and affordable	The magnitude of premiums is to be determined from further research.	Higher insurance premiums will be needed to cover productivity losses.	Premiums likely to be unaffordable if market losses are insured.
	(8) *Cover limits*—must be acceptable	Cover limits defined in emergency response deeds.	Cover limits would be required.	Cover limits would be required.
Societal	(9) *Public policy*—consistent with societal values	Consistent with proposed reform to legislation for an import levy.	As per response loss assessment.	As per response loss assessment.
	(10) *Legal restrictions*— coverage allowable	Biosecurity insurance would need to be mandated because of the negative biosecurity externality.	As per response loss assessment.	As per response loss assessment.

Table IV. Additional HBH Insurability Criteria Assessed Against Biosecurity Risk

Category	Description	Response losses	Productivity losses	Market access losses
Actuarial	(1) *Loss assessment*—able to estimate frequency and magnitude	*Frequency of biosecurity risk incursions*—may be able to adapt existing RRRA process being developed by the Commonwealth. *Magnitude of losses*— existing methods such as AADIS (Bradhurst et al., 2015) have been developed to measure the magnitude of containment and eradication costs.	As per response loss assessment. *Magnitude of losses*—productivity losses moderately difficult to estimate. Assumptions required on transmissibility and impact leading to variation in estimates.	As per response loss assessment. *Magnitude of losses*— market loss difficult to estimate accurately. Economic models exist but rely on uncertain assumptions leading to wide variations in estimates of market access losses.
	(2) *Definition of loss*—circumstances of loss definable	The nature of risk is clearly defined in terms of response and eradication strategies. These are specified in the emergency response deeds.	The nature of risk is less clearly defined. Productivity losses will vary across business units and according to the biosecurity threat.	Loss of market access is observable and easy to define. Specific biosecurity threats are known to trigger market access loss in international markets.

mandate that importers purchase insurance against losses arising from introduced biosecurity threats.

4.2. Actuarial Insurability Criteria

Berliner identified six actuarial criteria that influence the insurability of risk (Table III). The first is the *randomness of loss occurrence*. It refers to the probability that losses incurred by one establishment are a random draw from the risk pool and independent of loss occurrence by other establishments.

In the biosecurity context, response losses arising from effort needed to detect, control, and eradicate pests and diseases that breach national borders are likely to occur randomly (i.e., $\rho = 0$). This is because *entry* of pests and diseases in import consignments appear to be independent and random even though the probability of entry will vary depending on the type of good, country of origin, and so on. However, loss occurrences from productivity and market exclusion display systematic (positive) correlation once pests and diseases *establish* and *spread*. For pests and diseases, such as foot and mouth disease (FMD), loss occurrence on one establishment will be perfectly correlated with losses on other establishments because infection of just one herd will lead to loss of market access for all herds. The correlation coefficient (ρ in Equation 2) for this type of loss occurrence will assume a value close to 1, eliminating scope for risk pooling and rendering the risk uninsurable. The 1997 outbreak of FMD in Taiwan (previously the world's largest pork exporter) is an example of nation-wide loss of market access (see, Felt, Gervais, & Larue, 2011, and Hennessy & Wolf 2018).

Randomness of productivity loss occurrence is likely to be influenced by the transmissibility of pests and diseases. Highly transmissible[8] pests and diseases will cause loss occurrence to be highly correlated although a range of factors such as the structure of production units, effectiveness of movement controls, and other epidemiological interventions will mitigate transmission rates influencing the randomness of productivity loss occurrence. For example, the Australian pig industry is based on closed production systems (i.e., minimal disease piggeries) in which movements of animals (and diseases) can be controlled between establishments. Under these circumstances,

[8] Transmissibility of diseases is measured as a transmission coefficient. It defines the rate that disease moves from infected individuals to susceptible individuals in the population and is measured on a scale between 0 and 1.

productivity loss occurrences from even highly transmissible diseases may be restricted to individual production units. At the other extreme, WSD devastated a regional Australian prawn industry because prawn farms shared a common waterway allowing the disease to spread rapidly and widely (IGB, 2017).

A second actuarial consideration is the *predictability of loss occurrence*. Response losses appear to be relatively predictable, particularly where response actions are specified in the various emergency response agreements and deeds (discussed in Section 2). Bradhurst et al. (2015) for example, have developed a methodology for estimating response costs through an agent-based epidemiological model. Market access and to a lesser extent, productivity loss occurrence, appear to be more difficult to predict. While economic techniques have been developed to measure some types of loss occurrence in some sectors of Australia (e.g., Buetre et al., 2013; Cook, 2019; Cook, Thomas, Cunningham, Anderson, & De Barro, 2007; Do & Vanzetti, 2018; Kompas, Ha, & Spring, 2015 for losses to the agricultural sector), loss estimates vary widely (particularly for market access losses) and there are difficulties in measuring environmental and amenity losses. An example of the inconsistency in estimating market access losses can be seen in Buetre et al. (2013) where the maximum possible loss from FMD is estimated to be between \$5.2 billion and \$52 billion over 10 years. Lack of confidence in the predictability of loss occurrence is cited by Cook et al. (2007) to explain the absence of private biosecurity risk insurance products.

A third actuarial complexity developed by Berliner is *maximum and average loss*. Risks exhibiting maximum losses that exceed the capacity of the risk capital of an insurance company are considered uninsurable. Based on estimates from Bradhurst et al. (2015), market access losses are typically higher than productivity losses, with response losses representing the lowest amount. The *average loss per event* can be expected to be ranked in the same way.

The final actuarial criteria outlined by Berliner concerns *information asymmetry*. Information asymmetry causes two types of problem in the insurance context: (i) adverse selection and (ii) moral hazard. Information hidden from the insurer prior to the allocation of insurance contracts (hidden information) causes adverse selection problems in which the wrong contract is allocated to the insured. Efficient allocation of insurance contracts depends on truthful revelation of information such as the risk properties of different actions and appetite of the insured for risk-taking activities. If these information problems cannot be addressed, they influence the magnitude and frequency of payouts and the viability of insurance. A second information asymmetry problem can arise after the allocation of contracts because the insurer cannot observe all actions of the insured. It is referred to as the hidden action, or moral hazard problem.

The adverse selection problem is likely to be important where insurance premiums reflect biosecurity risks as this creates an incentive for importers (the insured) to appear to be low-risk types so they pay lower premiums. Nonverifiability of agreed/required preborder biosecurity interventions, such as the declared status of imports with respect to origin; completion of inspection and treatment actions; description of goods on the import manifest; and the validity of certification proclamations, will influence the risk assessment of the insurer. This information is difficult to verify in an environment in which there are high volumes of imports and low sampling fractions. Nonverifiability will be an important information consideration in the design of a biosecurity risk insurance mechanism. It is noted that this is a common problem with other insurance markets.

Moral hazard (the hidden action problem) appears to be of lesser importance with respect to biosecurity risk. The negative biosecurity risk externality problem, identified in Section 3, means that there is no incentive for either the risk creator (importer) or the risk bearer (e.g., primary producer, environmental manager) to take actions (e.g., deliberately releasing a pest or disease) that would trigger insurance payouts. This feature of biosecurity risk leads to an unusual insurance model, which is discussed in detail in Section 5.

HBH introduce two further actuarial criteria that determine the insurability of risk. These concern the ability to assess the *frequency* and *magnitude of losses* before risks can be insured. As summarized in Table IV and Section 2, methods and techniques have been, or are being developed within existing biosecurity institutions to assess the frequency and magnitude of a range of biosecurity threats and could be adapted to an insurance framework. These capabilities are more reliable and suited to estimate response losses than productivity and market access losses.

The ability to *define losses* is the final criteria identified by HBH. Our initial assessment is that response losses and market access losses are definable, but productivity losses appear to be less so. In

Australia, response losses are, or can be, defined and specified in the emergency response plans for plant and animal pests and diseases. Similarly, the pests and diseases, such as FMD and mad cow disease (bovine spongiform encephalopathy), that trigger market access loss are obvious and definable under WTO agreements. Productivity losses are less definable because they are specific to different biosecurity threats and production systems.

4.3. Market Insurability Criteria

The final insurability criterion concerns the *affordability of insurance premiums* and the feasibility of *cover limits*. In the absence of further research to estimate the likely magnitude of insurance premiums for a range of imported goods, it is not possible to determine affordability of premiums. However, insurance premiums needed to fund response losses will be lower (more affordable) than those for insurance schemes that cover productivity and market access losses. Affordability is less of a concern in the biosecurity context because national welfare will be increased if goods that have high biosecurity risk, and consequently unaffordable premiums, are not imported. Finally, there are no apparent foreseeable limitations to imposing cover limits for response, productivity, or market access losses.

4.4. The Boundary of the Market for Biosecurity Risk

Markets for biosecurity risks are missing in the Australian economy primarily because importers are not compelled to bear the financial consequences of these risks. Even if this barrier were removed via changes to national legislation, our application of the Berliner and HBH criteria suggest that not all losses occurring from biosecurity risks appear to be insurable. The boundary of the risk markets in the national biosecurity context appears to lie between response losses and productivity losses. Losses arising from effort needed to detect and respond to exotic pests and diseases that breach national borders appear to be insurable because the entry of biosecurity threats that trigger response losses appear to be largely random events; loss occurrence is relatively predictable from existing modeling and data systems; losses can be defined through pest- and disease-specific response plans; and losses may be capped through these deeds if needed. While further research is needed to determine the affordability of insurance premiums, it has been noted that unaffordable insurance premiums (denoting high risk imports) will initiate behavioral responses that are in the national interest. As pests and diseases establish and spread, market access losses appear to be uninsurable and productivity losses become less insurable where pests and diseases are highly transmissible. The insurability of productivity and market access losses is also weakened by other insurability criteria such as: the unpredictability of expected losses, particularly market access losses; the extent to which maximum possible losses are unmanageable; and the affordability of insurance premiums. These may be partly addressed by introducing features such as: caps on coverage, multilayer risk transfer systems involving primary insurers, reinsurers, retrocessionaires,[9] and capital markets; and through government interventions to boost insurance capacity. It is noted that risk transfer structures have proven effective in the catastrophic risk insurance market where both frequency and severity of losses are similarly difficult to predict. Advances in modeling catastrophic risks (e.g., insurances for terrorism risks) could also have application to biosecurity risk and may change the boundary of biosecurity risk markets (see, Grossi & Kunreuther, 2005; Eling & Schnell, 2016; Major, 2002; and Betterley, 2018).

5. IMPLEMENTATION ISSUES

Fig. 1 illustrates how an insurance approach might be implemented and integrated into the existing biosecurity system. In this diagram, uninsurable biosecurity risks (i.e., those causing productivity and market access losses) would be managed through the existing centralized approach in which government regulates pre- and at-border risk mitigation effort, allocates resources, and self-insures against these risks.

Insurable risks (i.e., response losses) would be managed through risk markets (a decentralized mechanism) in which the price of risk is revealed to importers as insurance premiums, creating incentives for them to align import decisions with national biosecurity objectives. This approach fundamentally changes the way biosecurity risk is managed and funded. One feature of this approach is

[9] A retrocessionaire is a reinsurance company that takes on part of the risk assumed by another reinsurance company. Retrocession aims to reduce risk and the liability burden of the initial reinsurer by spreading out the risk to other reinsurance companies.

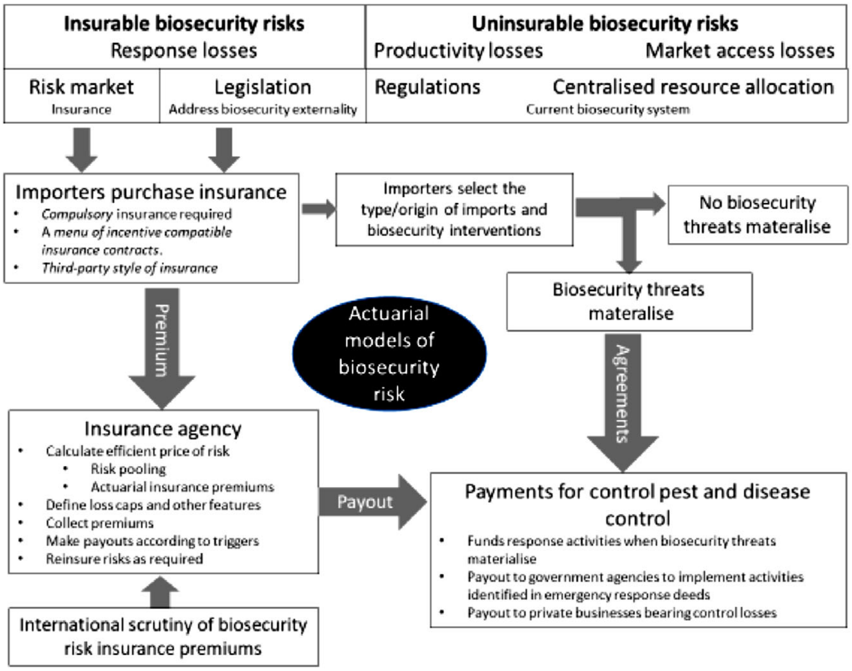

Fig 1. Preliminary architecture of a biosecurity insurance scheme.

that insurance premiums paid by importers (risk-creators) would fund the losses incurred in controlling pests and diseases that breach national borders. This contrasts with most biosecurity systems where risk-bearers, including government disease management agencies and primary producers fund control activities. Unlike insurance against personal loss and injury (e.g., house and contents insurance), biosecurity risk insurance on imported goods would need to be compulsory (to address the negative biosecurity externality problem, discussed in Section 3) and payouts would be made to third-parties that incur costs arising from pest and disease control activities (risk-bearers). This mechanism is analogous to compulsory third-party person insurance where motorists insure against injury to others. The components of this mechanism identified in Fig. 1 are discussed in more detail in the following sections.

5.1. Importers Purchase Insurance

Fig. 1 indicates that insurable biosecurity risks (i.e., response losses) would be managed by creating biosecurity risk markets based on the risk pooling and actuarial pricing principles discussed earlier in the article. Legislation mandating that importers purchase biosecurity risk insurance would be needed to address the biosecurity risk externality problem. Compulsory participation would also guarantee a portfolio size (n) in excess of the critical mass (the value on n beyond which diversification benefits become material).

Information about the price of biosecurity risk for alternative import strategies could be presented to importers as a *menu of incentive compatible insurance contracts*. Menus of contracts are commonly used in the insurance sector to allow the insured to combine private information (e.g., about their appetite for risk) with the cost of risk for different risk-creating activities. For example, motorists are offered a menu of premiums and excess payments to improve matching to the "best" insurance contract (the adverse selection problem). Data permitting, actuarial pricing of biosecurity risk for each type of good imported (e.g., types of plant and animal products), its origin, and investment in biosecurity interventions preborder and at-border would be revealed to importers as a menu of premiums. Importers would then combine information about the price of biosecurity risk with private information they hold about profit margins, to identify the optimal import pathway. For example, items imported from countries free of relevant biosecurity threats would attract lower premiums than the same item imported from high risk countries. This approach creates incentives for importers to search for import pathways that maximize national welfare.

The *third-party style of insurance*, noted above, maintains incentives for beneficial behavioral change (selecting optimal import pathways) but avoids a range of technical, legal, financial, and timeliness problems that would apply if individual importers (with insurance) were to be held responsible for funding pest and disease control losses. Assignment of biosecurity risk to individual importers in not practical because traceback technologies are unlikely to establish legally binding attribution of biosecurity risks; legal processes would slow down pest and disease response programs increasing the cost of these programs; and control costs for pest and disease incursions are likely to exceed the financial capacity of individual importing businesses.

5.2. Insurance Agency

An insurance agency would need to be created to set and receive premiums from importers and make payouts needed to fund response activities as incursions arise. As noted earlier, further research is needed to adapt actuarial principles to biosecurity, define loss caps, identify underwriting strategies, and so on. Preliminary analysis suggests that information about risk exposure (the RRRA model established by the Australian Government) and epidemiological modeling capabilities (e.g., the AADIS hybrid model) already exist and could be adapted to provide estimates of expected losses.

It is not clear whether the insurance agency would be managed within the public domain or by the private sector. If the insurance agency and its functions were contracted-in, government would calculate insurance premiums, reveal these to importers (as a menu of insurance contracts), establish and manage the insurance pool, and assess and pay claims to fund response activities as they arise. Alternatively, these functions could be contracted-out, in which case government would mandate the purchase of insurance, however, premium setting, fund management, and payout functions would be provided by private insurance businesses. In this case, premiums would be loaded with a profit factor so that the private insurer's cost of capital can be recovered. As with all such decisions, transaction costs will determine the "best" approach. Insights relevant to these alternative approaches can be expected from research into the information systems needed to estimate biosecurity risk insurance premiums; the political economy with respect to government's role in underwriting biosecurity risks; and the synergies between the current biosecurity system and a biosecurity risk market. Whether constituted as a public or private organization, the insurance agency must harness the relevant skills needed to calculate insurance premiums, hold enough capital to ensure it can make compensation payments even if losses are (much) greater than expected and monitor the actions of importers. These complexities are common to other classes of insurance but underlying risk metrics (e.g., "value-at-risk") and processes to address adverse selection and moral hazard problems will need to be developed.

5.3. Payments for Pest and Disease Control

Payouts from the insurance pool would be made to the third parties identified in the emergency plant and animal response deeds (noted in Section 2). These deeds define the actions needed and agents responsible for detecting, controlling, and hopefully eradicating introduced pests and diseases before they establish and spread. These agreements would need to be reviewed in an insurance context to ensure that they are financially sustainable and incentive compatible. They would need to clarify payout triggers, define loss limits, and refine the incentives structure of payouts to mitigate adverse selection and moral hazard problems. For example, payouts that are too generous may encourage some primary producers to deliberately introduce biosecurity threats (a hidden action problem) and payouts that are insufficient will discourage producers from revealing information needed to efficiently control pests and diseases (a hidden action problem).

5.4. International Trade Considerations

From an international trade perspective, an insurance approach must manage the tension between the interests of vested parties (e.g., domestic producers who would benefit from higher risk premiums on imported goods) and the welfare costs of such strategies. At a theoretical level, actuarially-based biosecurity risk insurance should be attractive to the WTO because biosecurity risk is a legitimate component of the cost of imports and is intended to achieve an efficient, as opposed to an appropriate level of protection (ALOP), as is the current convention. An insurance approach may offer a higher level of transparency with respect to the misuse of biosecurity as a nontariff barrier to trade. For example, countries that allow premiums to be set too high (a tax on imports) will create large, but observable, balances in the insurance pool. Similarly, biosecurity risk premiums on imported goods could also be compared between countries as an indicator of their misuse as a nontariff barrier.

6. DISCUSSION AND CONCLUSIONS

Protecting economies from biosecurity threats is a costly but necessary activity. The Australian Government currently invests significant resources to mitigate biosecurity threats via direct investments, regulation, and risk management activities. Important efficiency and efficacy gains could be achieved by augmenting this system with biosecurity risk insurance in which importers are required to purchase insurance. In this article we find that the boundary of such a mechanism is influenced by the type of losses covered. Losses that occur because of the effort needed to respond to, contain and eradicate biosecurity threats inadvertently introduced with imports appear to be insurable; productivity losses become less insurable as the transmissibility of pests and diseases increase; and loss of access to export markets appears to be an uninsurable risk because of high levels of systematic risk, difficulties in predicting and estimating losses, and concerns about their associated irreversibility.

The primary advantage of an insurance-based mechanism to manage response loss occurrence is that it reveals efficient prices for biosecurity risks created from imported goods. This approach contrasts with the current biosecurity system in which the "price" of biosecurity risk is implicitly determined through various risk sharing agreements established between different levels of government and industry. In this system, financial sustainability is achieved through funding agreements rather than actuarial pricing principles. The economic efficiency gains from revealing efficient prices of biosecurity risk (relevant to response loss occurrences) can be expected to be significant given the volume and value of imports and the cost of biosecurity response effort. These gains would arise from the information and incentive properties of a decentralized mechanism in which importers are rewarded for discovering import pathways that optimize both private and national interests. The mechanism has financial sustainability advantages because the revenue raised from actuarially determined biosecurity risk insurance premiums would be structurally linked to the expected cost of implementing activities needed to respond to biosecurity threats. It also has equity implications because risk creators (importers) fund response effort.

The research reported in this article does not establish whether it is feasible to create a market for biosecurity risk associated with response losses, whether such a mechanism is implementable within a national biosecurity system, or provide estimates of the economic efficiency gains that could be expected. Rather, this article's findings justify further research to explore these issues. A second phase of research is planned in which an actuarial insurance model for biosecurity risks will be developed and insurance premiums estimated for selected imports. Issues including the feasibility of adapting existing biosecurity risk data systems and epidemiology models to estimate insurance premiums will be determined in this phase. A final phase of research is anticipated in which a randomized control trial methodology would be applied to estimate expected economic efficiency gains. The main findings reported in this article are that the response losses arising from introducing biosecurity threats are insurable and the information and incentive properties of this approach establish a foundation for economic efficiency gains.

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