PUBLIC-PRIVATE PARTNERSHIPS FOR THE MANAGEMENT OF PLANT PESTS

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Abstract

The number of plant disease and pest outbreaks is increasing rapidly as a consequence of globalisation and climate change. Developing efficient and effective management plans for prevention and control is of key importance to avoid economic, environmental and human health impacts. Private-public partnerships (PPPs) for biosecurity are policies where the public and private sector agree on a division of the costs and responsibility obligations for action and control prior to an outbreak. It has been argued that PPPs can encourage a consistent and coordinated management approach to biosecurity, thus facilitating early response and achieving economies of scale that otherwise would not be possible. This thesis aims to inform the design of collaborative and contingent PPP to manage pests and diseases, particularly focusing on how to incentivise private investments in biosecurity. The thesis is comprised of three interconnected research projects exploring three key elements of PPPs: risk and responsibility sharing, cost sharing, and private agent preferences for engagement within such schemes. I used three different methodological approaches, contract theory, game theory, and choice experiments to model agent behaviours and interactions between the public and private sector. Key findings show the following: *(i)* a cost and risk sharing approach can deliver increased biosecurity by having government contingent compensation payments to private agents prior to outbreaks; *(ii)* tailoring plant health policy between pure and impure public goods can lead to more cost-effective schemes; *(iii)* targeting schemes to best serve the needs of agents by, for example, partially subsidising industry and national initiatives, developing more flexible, simplified and consolidated policies, and incentivising stakeholder engagement in policy design. The thesis also provides a foundation to stimulate further applications of contract theory, game theoretical methods, and choice experiments to answer important policy questions regarding biosecurity.

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Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References. All data analysis and writing of this thesis is my own work. The contribution of co-authors for published or under review papers are detailed as follows.

Chapter 2:

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The contribution by co-authors was as follows:

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Chapter 1 – Introduction

1.1 Chapter summary

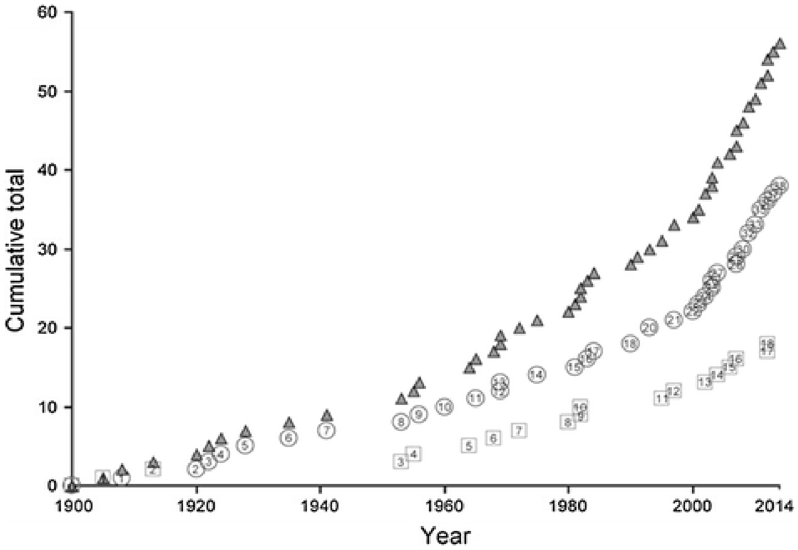
This Introduction chapter provides the background and rationale for the thesis and summarises the aims and objectives addressed in the later chapters. The chapter starts with a discussion around the challenges of plant pest management and provides a brief overview of different policies and instruments commonly used. Then, a case is made for the use of public-private partnerships (PPPs) as an effective and efficient approach to biosecurity. A non-comprehensive list of PPPs case studies illustrates key elements of this policy tool, which are used as motivation for further exploring different aspects of PPPs in later chapters. Lastly, the objectives, research approach, and main contributions of each chapter are outlined.

1.2 Background and context

The number of pest and pathogen outbreaks and biological incursions has been increasing in recent years (Freer-Smith & Webber 2017; Anderson et al., 2004; Brasier, 2008; Chapman, Purse, Roy & Bullock, 2017; Hulme, Nentwig, & Pyšek, 2009). About 50.000 species are estimated to have been introduced in the US alone (Pimentel et al., 2005). In Europe, the total number of pest species has increased, and an estimated 11,000 alien species have crossed Europe's borders (Hulme, 2009; DAISIE, 2009). Taking as an example the case of tree pests and pathogens in the UK, Freer-Smith and Webber (2017) estimated a cumulative total of 56 new introductions. When the recordings are plotted over time, there is a substantial increase in introductions over the last three decades (see Figure 1.1).

The upsurge in introductions over recent years has been driven primarily by greater international trade due to globalisation (Ding, Mack, Lu, Ren & Huang , 2008; Bacon, Aebi, Calanca & Bacher , 2014; Flood & Day, 2016), and by climate and environmental changes (Bebber et al., 2014; Bebber, 2015). Higher connectivity has greatly increased the frequency and magnitude of pest outbreaks around the world by facilitating the long-distance movement of species into regions outside of their historical range (Ricciardi, 2007). Thus, the movement of plants, trees and derived products has accelerated the increase in novel encounters between host and pathogens. For example, the international trade in live plants is estimated to be responsible for 70 % of tree pests entering the US (Liebhold, Brockerhoff, Garrett, Parke & Britton, 2012). Consequently, the probability of invasive species emergence has increased, to the point that some authors have argued that disease outbreaks and pest invasions are likely to become permanent features of the Anthropocene (Potter & Urquhart, 2017; Lovett et al., 2016; Brasier 2008; Eyre et al. 2013; Evans 2014). Additionally, climate change is expected to exacerbate the problem by creating opportunities for further spread as organisms previously constrained by low temperatures are likely to expand their range (Crowl, Cris, Parmenter, Belovsky, Lugo, 2008). More frequent extreme weather disturbances such as storms or droughts are also likely to provide further opportunities for pest outbreaks to flourish (Evans, 2014; Tobin, 2015).

Figure 1.1 Cumulative numbers of new tree pathogens (*circle*), insect pests (*square*), and accumulated total (*triangle*) in the UK since 1900. Source: Freer-Smith & Webber (2017).



A large proportion of all known species introductions have been intentional and many such species are now economically important. For example, Pimentel et al. (2005) estimated that approximately 98% of US food is produced by invasive species, and this production is valued at approximately $800 billion per year. According to the ‘tens rule’ (Williamson & Fitter 1996), approximately only one in ten introduced species are likely to be able to establish; of these, a similar proportion (10 %) will result in large economic costs, including damages to ecosystems, impact to the production and consumption economy, and costs of eradication and control. For example, the US spent an estimated $590 million in 1999 to prevent and control invasive species, and the UK spent approximately $111 million in 2000 on animal and plant health (Mumford, 2002). However, these numbers only account for control measurements. Total damage is estimated to be much larger, particularly if other, less easily quantified impacts are included (Pimentel et al., 2005). For example, invasive forest pests and diseases can significantly impact ecosystem services, such as reducing biodiversity and wildlife habitats, altering natural landscapes and their recreational or cultural value, as well as affecting the ability of forests to sequester carbon, protect watersheds or combat desertification (Boyd, Freer-Smith, Gilligan, & Godfray, 2013; FAO, 2009; Potter & Urquhart, 2017). Pimentel, Zuniga and

Morrison (2005) estimated the economic costs associated with invasive species in the United States, and the loss rises to almost $120 billion per year. A recent study found that the total cost of Ash dieback alone to the UK is estimated to be £15 billion, with the loss of ecosystem service benefits provided by trees being the biggest cost to society, in addition to billions of pounds needed to clear up roads and urban areas (Hill et al., 2019).

However, as Perrings et al. (2002) stated, the challenge is not to precisely estimate the costs, but instead to develop efficient management plans for the prevention and control of pests to avoid further damages to both the economy and the wider ecosystem. Designing and implementing effective policies though has proven to be a difficult challenge. The management of pests exhibits certain features that distinguishes it from typical markets (Olson, 2006). Thus, understanding the economic underpinnings of biosecurity efforts is crucial to identifying the challenges and developing efficient and effective policies.

In economic terminology, policies to manage pests often exhibit a “public good” nature (Graham et al., 2019; Perrings et al., 2002; Hennessy, 2008; Touza & Perrings, 2011). This means that the provision of biosecurity efforts can be non-rival and non-excludable, allowing stakeholders to derive biosecurity benefits without having to face the costs or detracting other’s enjoyment thereof (Kruger, 2016; Graham et al., 2019). For example, plant nurseries who engage in high risk activities often only account for the risks affecting themselves and do not take into consideration the risks they impose on others, such as other agents in the supply chain or the wider society (Lasink, 2011). Additionally, outbreaks management efforts are also considered externalities (when the decision of one agent has an impact on the welfare of others) because of the failure of markets or regulatory institutions to account for all the damages the pests may cause to society (Touza, Dehnen-Schmutz & Jones, 2007). The “public good” element of plant health and existence of externalities induce a strong incentive to free-ride on the management efforts of others, and it often results in the under-provision of biosecurity.

Outbreaks are often characterised by having a complex socio-ecological network component. While close cooperation among stakeholders is often necessary to successfully manage pests, the propensity to collaborate is expected to differ from case to case as the socio-economic, ecological and biophysical conditions may vary substantially (Graham et al., 2019; Epanchin-Niell & Hastings, 2010). For example, ecosystem interactions in the environment determine the rate of spread and may not allow for an invasion to be successful (Lodge, 1993; Lawton & Brown, 1986; van Kleunen, Dawson & Maurel, 2015). In addition, management efforts are often conducted by many actors, such as environmental organisations, growers, agricultural producers, or gardeners, each with different risk preferences regarding plant health. Reaching an agreement about biosecurity actions under such potential heterogeneity of agents is a challenge (Waage, Mumford, Leach, Knight & Quinlan, 2007).

This network of agents interacting with each other is often described as having a weaker/weakest link property (Touza & Perrings, 2011; Burnett, 2006). The control of the spread is only as good as the control of the worst agent in the network, or in the case of weaker link, individual contributions beyond the lowest level will provide benefits but the benefits progressively decline as contributions exceed minimum. For instance, the control and eradication of an invasive plant across a landscape will only be as effective as the efforts of the least effective landowner. Perrings et al. (2000) also illustrated the weakest link property at a national scale, when export markets are accessible if a country is free from a pest or disease but the plant health status could be lost due to a single importer with low standards. Given these network characteristics, agents are likely to make strategic choices about biosecurity according to the actions of others.

The effective management of pests is often limited by the uncertainty about economic (e.g. the expected value of damages of an outbreak as this can be driven by price changes in the affected crops), social (e.g. communication among stakeholders), and biological parameters (e.g. the state of the outbreak or potential spread and establishment), which hinders the design of biosecurity policies (Cook, Liu, Murphy & Lonsdale 2010; Epanchin-Niell & Hastings 2010; Saphores & Shogren, 2005; Mumford, 2011; Melbourne & Hastings, 2009; Mauelshagen et at., 2014). A particular information related challenge occurs when stakeholders face different levels of information, known as asymmetric information, and it can result in a problem of moral hazard and adverse selection (Pauly & Blavin, 2008; Lansink, 2011; Laffont, & Martimort, 2009). Moral hazard occurs when agents change their behaviour after agreeing to a transaction because they believe that they do not have to face any consequences for their actions. Adverse selection occurs when, in an agreement, one agent has more accurate information than the other party does. For example, in a plant health scenario, adverse selection may occur if growers have more information about the biosecurity quality of plants than the customers, and moral hazard when farmers take on more risks after purchasing insurance.

Lastly, certain type of outbreaks, such as quarantine pests, can cause special problems for markets because of their systemic nature and the asymmetric information problems faced by insurers (Miranda & Glauber, 1997; Esuola, Hoy, Islam & Turvey, 2007). These outbreaks can be categorised as catastrophic events, and thus, cannot be managed efficiently on competitive markets (OECD, 2005). For such low frequency but high damage risks with systemic nature across the industry, public intervention is often required for the development of successful risk management strategies (Miranda & Glauber, 1997; Goodwin, 2001; Wright, 2014).

The challenges and market failures described hinder effective pest prevention and control efforts, by creating a gap between what private individuals are willing to contribute towards management efforts and the social optimal level, leaving biosecurity efforts often underprovided and mismanaged (Perrings et al., 2002). Thus, government intervention is often needed to secure a minimum of biosecurity efforts taking place (Khan, 1998). The government has a series of instruments available to engage stakeholders in their effort contributions and correct for the difference between the socially optimum level and the optimal private provision. Such measures include economic incentives, command and control, and voluntary instruments. Table 1 provides an overview of policy approaches and how they attempt to tackle some challenges.

Table 1.1 Overview of instruments to manage pests and outbreaks.

	Underprovision	**Cooperation**	**Heterogeneity of stakeholders**	**Uncertainty**	**Implementability and social acceptability**
Voluntary Approaches	Voluntary approaches alone tend to not encourage enough biosecurity efforts	Large problems to ensure that everyone invests in biosecurity	Adapts easily to the risk preferences of each stakeholder, since no behaviour is imposed.	Not flexible to encourage early action when dealing with new incursions	Easy to implement and widely accepted among all type of stakeholders
Command and control	Probably the most likely type to attain higher biosecurity efforts	Takes care of multi-stakeholder involvement	Enforces the same behaviour for everyone	Not flexible to new invasions	Easy to implement but not widely acceptable
Economic incentives	Good in theory, but difficult to achieve in the real world	Focuses on individual behaviour rather than combined efforts	Allows for different optimal behaviour depending on agent's preferences	Sort of flexible to unforeseen damages	Hard to implement and usually not very accepted by stakeholders

Command and control legislation has often been the foundation of pest policies in many countries, including Australia (Parsons and Cuthbertson, 2001), and the United States (Zellmer, 2000). Command and control instruments include the use of fines and specification of liabilities, declaration of illegal behaviours that can potentially increase the risk or spread of an outbreak, and use of penalty payments as incentives to comply with regulations. An example of command and control is the current regulation to prevent and control the spread of *Xylella fastidiosa*, a multihost plant pathogen with likely impacts to include non-market ecosystem damages as well as commercial production losses (EFSA Panel on Plant Health (PLH), 2019). EU crop protection regulations apply, with long-term movement restrictions in the radius of 10km around known outbreaks, lasting for as long as 5 years (Forestry Commission, 2018). An advantage of command and control is that they allow recovery of part of the costs of an incursion from liable parties that have breached the specified regulation. However, they are rigid policies that often struggle to deal with new unforeseen invasions (Mumford, 2011). Additionally, they often lack acceptability by stakeholders due to the imposition of restrictions rather than the use of incentives (Kahn, 1998).

Voluntary schemes like biosecurity-related assurance schemes, certification schemes and codes of conducts, where suppliers share some voluntarily agreed set of standards, are an alternative approach to the commonly used compulsory regulations which have gained increased interest recently (DEFRA, 2018b; HTA, 2017; DEFRA, 2011). The voluntary guidelines can be directed to either private individuals, industry or to governments, and are not mandatory so agents are not forced to change their behaviour. Instead, the goal is to inform about the implication and potential future impacts of their biosecurity actions, with the hope that the agents themselves would change their preferred way of action. The effectiveness of such voluntary approaches has been questioned because of the lack of incentives to comply with the shared standards and sanctions (Lyon & Maxwell, 2001). Moreover, voluntary schemes can suffer from limited membership and consequently fail to have a significant impact (Wolf, 2005; Moss & Walmsley, 2005). Voluntary efforts can be attractive instruments though, because they encourage a pro-active cooperation approach from the private sector and reduce potential conflicts between the regulator and the industry (Segerson & Miceli, 1998). In addition, they tend to be focused on prevention efforts and are flexible in terms of management, thus capable of dealing with uncertain scenarios (Segerson & Miceli, 1998).

Lastly, economic instruments aim to create incentives that change the behaviour of agents. While the use of economic incentives to improve the management of pests has become popular in the academic literature (Horan & Lupi, 2005; Jones & Corona, 2008; Costello & McAusland, 2003; Costanza & Perrings, 1990), their use in the real world is more limited. Reasons for difficulty in their implementation include their requirement of large amounts of information about agents’ behaviour and preferences, their sensitivity to economic fluctuations, and noncompliance with international trade agreements. Yet, there are some examples of such economic instruments in a biosecurity setting. These may involve taxation such as Hawaii’s conveyance tax on real estate transactions, which is allocated to the Natural Area Reserve Fund (NARF) and used for the prevention and spread of invasive species (Hawaii Senate Bill, 2005). Additionally, subsidies are used in Argentina to manage the invasion of Canadian beaver (Management of Canadian Beavers in Argentina, 2008), rewards for risk consideration are used to incentivise good behaviour of importing agents in Australia (Daff Annual Report, 2012-2013), and the Tree Protection Bond of the US town of Vienna[1].

1.3 Public Private Partnerships

1.3.1 A motivation

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[1] https://www.viennava.gov/index.aspx?NID=98

A common theme across the previously described instruments and policies to manage pests is that most tend to focus on post-incursion action. Since budgets are limited, resource managers often allocate funds to the most immediate and visible problems, thus prioritising control over prevention (Finnoff, Shogren, Leung & Lodge, 2007; Kaiser & Burnett, 2010). However, early detection and rapid action are usually considered major factors in mitigating impacts of pests (Kaiser and Burnett, 2010). For example, New Zealand successfully intercepted *Solenopsis invicta* and *Lymantria dispar* at the border (Kaiser & Burnett, 2010). As a result, focusing on prevention methods and encouraging rapid action is generally recognised as being more effective, in terms of costs and mitigating the damages of invaders, rather than spend efforts eradicating or controlling invaders (McNeely, Mooney, Neville, Schei & Waage , 2001; Leung et al., 2002; Heikkilä & Peltola, 2004; Sims & Finnoff, 2013).

Additionally, current prevention and response activities to incursions are generally inconsistent and uncoordinated and tend to lack acceptability among stakeholders (Mumford, 2011; Cook et al., 2010). Jurisdictions depend on usually poor surveillance to detect new incursions, and there is limited understanding of the pathways of introduction and spread (Mumford, 2011). Moreover, the roles and responsibilities of agencies are sometimes not clearly defined, and there tends to be a lack of basic emergency response actions readily available (Cook et al., 2010).

The need for a more engaging policy targeted to both early action control and prevention methods is increasingly recognised, particularly as the risks of invasions increase as the trade production networks become more complex (Perrings, Burgiel, Lonsdale, Mooney & Williamson,2010; Hulme et al., 2009). Recently, policy makers have acknowledged the limitation of previous efforts and that new approaches that embrace shared responsibility and costs between the private and public sector are needed (Roy et al., 2012; DEFRA 2018b; New South Wales Natural Resources Commission, 2016). For example, the UK's 25-year Environment Plan includes the objective to "make biosecurity central to all buying decisions" (DEFRA, 2018a), and the new "Plant Health Law" (European Parliament regulation2016/2031), a new regulation aimed at modernising the plant health regime in the EU and to ensure safe trade, is entering into force at the end of 2019.

A program that incorporates private and public agreements to detect, control, and manage the impacts of invasions is often referred to as a 'biosecurity' program, and it is often described as a good management practice (Mumford, 2011; Anderson, 2005; Cook et al., 2010). Biosecurity management agreements between the government and the private sectors to deal with outbreaks have the potential address some of the challenges previous instruments carry (Cook et al., 2010; Mumford, 2011).

Among the key advantages of this instrument is that it can provide incentives for higher private involvement in biosecurity measures, with the potential of gaining information on the status of the outbreak, building public-private trust, and improving communication among stakeholders. By sharing the responsibility between the public and private sectors, there is a sense of inclusiveness of all stakeholders involved, and a more complete network of support is developed (Cook et al., 2010). The development of such arrangements for incursions may reduce the risk of the entry and the spread of pests and will enable a consistent and coordinated management approach and will reduce costs in the long run (Mumford, 2002; Mumford, 2011; Cook et al., 2010). By joining efforts, landowners, managers, and the public sector can also achieve economies of scale and can develop combined strategies that would not be possible as independent agents (Krauss & Duffy, 2010). Lastly, from the private sector perspective, it could offer an alternative to more restrictive policies (e.g. ban on trade), and spreads the potential financial losses across multiple agents in the sector.

There is large a variety of different contingency PPPs, from government support to industry-based schemes, and cost sharing agreements, which divide the responsibility and costs of action and damage control between the public and private sector. For the purpose of this thesis, cost sharing is defined as the process of government and industry parties' splitting the costs arising from the implementation of biosecurity measures. These may include risk reduction and management, early response or eradication and control. Responsibility sharing is defined as the process of joint decision making of government and other stakeholders regarding measures for biosecurity. Hybrid approaches to the funding of control measures, i.e. neither entirely backed by government or industry, can take the form of, for example, a prospective fund, pre-agreed proportions of cost-shares or retrospective cost sharing.

Thus, contingent PPPs can sit across the three described instruments in Table 1.1, though most often include a combination of voluntary and economic incentives. By combining different incentive types, PPPs can capture meaningful membership sizes while providing the desired flexibility, adaptability, and a preventive focus. Determining the specific characteristics and structures of PPPs, and therefore which instrument is appropriate, may depend on various factors, including industry complexity, budget constraints, and whether expected damages are likely to affect beyond a particular industry. Regardless of the kind of contingency private-public partnerships, the common innovation across all PPPs lies in the combination of detailed agreements on how to prevent and respond to incursions and the legal commitment to follow these plans.

1.3.2 Case studies

This section highlights the schemes that motivated and informed the models developed in this thesis. The schemes introduced below illustrate how different PPPs have been established across the world, with the burden of cost and responsibility differing from one another. However, while these PPPs take different forms, they all have a crucial component in common: the development of an agreement stipulating the roles and responsibilities of both the public and private sector before an outbreak occurs. While the work in this thesis is motivated by these cases, the frameworks, models and results developed throughout the thesis could be generalizable to other cases. Therefore, this research provides a foundation to stimulate further contributions in developing PPP frameworks addressing the complexity in agent and government interactions to manage outbreak risks.

Australian Emergency Plant Pest Response Deed

In Australia, the Plant Health Australia Funding Amendment Act 2006 established a system for joint decision making between government and industry for each crop sector (Plant Health Australia, 2014). The system provides cost sharing based on a pre-agreed division of costs and responsibilities, with sector specific contracts called Emergency Plant Pest Response Deeds (EPPRD) between government and industry representatives. Government states and industrial partners sign a legally binding agreement, and they commit to follow the biosecurity plans decided. Based on where the expected pest impacts occur, a specific funding scheme is determined. For example, category 1 represents cases with high social impacts through their potential negative effects on ecosystem services and on trade relationships affecting multiple sectors in the economy, while category 4 represents invasions that only damage a particular crop and with no danger of disrupting the economy.

While many authors describe the EPPRD as an exemplary biosecurity system (Cook et al., 2010; Mumford, 2011), the framework has rarely been modelled and evaluated. One exception is Waage et al. (2007), who used a probabilistic computer model to show how different cost-sharing frameworks (one of them being a similar structure to the EPPRD) would affect the costs associated with a random outbreak and their associated risks.

Recognised Biosecurity Groups of Western Australia (RBGs)

The Biosecurity and Agriculture Management Act 2007 allows the Department of Agriculture and Food Western Australia (DAFWA) to recognise groups of stakeholders for their efforts in controlling declared pest at a landscape scale. The main goal of RBGs is to enable landowners to develop a coordinated approach by providing RBGs with a secure funding mechanism providing the basis for shared responsibility to control declared pests and enabling communities and industry to partner with a range of organisations, including state government agencies. Recognised groups establish their own pest action plans based on consultation and the plans and budgets are submitted to Department of Primary Industries and Regional Development (DPIRD) for review and approval. A Declared Pest Rate (DPR), set by the government based on discussions with stakeholders, is a rate determined on property/land in a prescribed area to fund activities to control established declared pests by the groups. The rate is set to raise half the money required by an RBG to fund their activities. The funds raised by the rates are matched dollar for dollar by the State Government under the BAM Act.

There are currently 14 formally recognised groups operating across Western Australia, with their combined areas covering most of the state (Government of Western Australia, 2019). Despite their recent success, RBGs have not been modelled or directly translated to other regions outside Western Australia. In 2017, the Western Australian Royalties for Regions funded a project to evaluate and gather insights about the process of setting an RBG in three case studies (Blackwood Biosecurity Inc., Northern Mallee Biosecurity Group and Peel Harvey Biosecurity Group) (Howard, Lawson and Coleman, 2017). However, the project focused on gathering experiences that could be helpful to communities who are thinking of forming a biosecurity group, rather than develop a theoretical model to optimally design a PPP scheme.

Subsidised public-private insurance systems

There are a few existing insurance-based cost sharing schemes implemented for quarantine plant health, but they tend to be found in less complex agricultural markets with limited externalities (Waage et al., 2007). For example, there is a full coverage government backed agricultural insurance programme in the USA, which includes coverage for potential losses from pests on insured farms, but it is not designed to cover additional costs associated with quarantine controls such as eradication operations. The participation rate is approximately 80% and this multi-peril insurance has been available since 1938 (Johnson & Monke, 2008). In Europe, the system of agricultural insurance in Spain is an example of a subsidised PPP, based on joint participation between public and private institutions. The State Entity for Agricultural Insurance (ENESA), an autonomous body linked to the Ministry of the Environment and Rural and Marine Affairs (MAPAMA), acts as the policymaking body creating the Annual Plan of Agricultural Insurance Policies, and determines the level of subsidies of insurance policies. Agroseguro is a private company owned by private insurers who participate in the scheme. The company is in charge of administering the insurance policies as well as claims and conducting the statistical and actuarial research. Farmers pay Agroseguro the net of the insurance subsidy, and Agroseguro receives the subsidy directly from ENESA and the regional governments.

Agroseguro, as one of the most advanced agricultural insurance systems across Europe, has been modelled and evaluated by many authors across the years. For example, previous literature that focuses on policy characteristics and agent preferences include Garrido and Zilberman (2008), Mercade et al. (2009) and OECD (2011), among others. OECD (2011) starts by providing a general overview of the subsidised private-public insurance system in Spain. Then it explores the split between private and public roles as well as how the insurance system operates in relation with catastrophic *ad hoc* payments. The report concludes by outlining policy implications for risk management and recommendations for the Spanish agricultural insurance system. Among those, of particular relevance for this thesis are the benefits of a hybrid public-private system with strong institutional support for risk reduction, improvement of financial performance and relative high participation rates by farmers. Mercade et al. (2009) used a choice experiment with farmers in the Catalonia region in Spain to understand the low participation ratio in vegetable crop insurance. The authors characterised the insurance policy by 4 main attributes, including cost; risks covered; minimum production damage level; and crop damage assessment rule. They found that the cost of insurance policies together with crop damage assessment methods are the principal factors driving farmers' behaviour. Lastly, using a different methodological approach, Garrido and Zilberman (2008) developed a stylised insurance model with constant absolute risk aversion preferences and yield moment generating functions. The model employs data from insurance records to explore motivations of farmers for crop insurance. They found that premium subsidies are the driving factor that increases the probability of purchasing crop insurance.

Government supported industry schemes

Another policy instrument is when the industry compensates its members for the costs of the outbreak. Scheme options could include a levy system, creating a mutual insurance fund the industry sector contributes on an agreed payment level to a common fund to cover costs of affected business during outbreaks, or a mutual insurance backed with government payments. This instrument acts as an insurance scheme to all members and spreads the costs among all members. One example of this system is the Dutch Potatopol Scheme, which is considered one of the most advanced insurance fund for quarantine plant health problems in Europe (Mumford, 2011). It is a combined prospective and retrospective fund, in which subscribers pay a fixed fee per area in advance but have an obligation to pay up to three times that fee in the event the fund falls short due to claims in a particular year. In this case, the government assisted with an initial grant of €250,000 to help establish the programme (Waage et al., 2007). Potatopol uptake is high and the level has been relatively consistent (Potatopol, 2018).

In their review of cost and responsibility sharing options for quarantine plant health, Waage et al. (2007) also explore government supported industry schemes, in particular the Potatopol Scheme. Their aim is to simulate a similar system to Potatopol for the UK potato industry. They develop a general framework model that allows coverage of a range of cost-sharing options. It also allows specification of distributions for outbreak frequency and magnitude, control costs, and potential vulnerable properties. It is important to note that in their simulations, only direct losses from quarantine action are covered and not any consequential losses. The authors find that there are no incentives for UK potato growers to join a mutual cost sharing scheme because diseases do not currently occur often to justify the payment.

Another recent example of an industry scheme is the currently being developed is the industry-led Plant Health Assurance Scheme (PHAS). Pilot studies and surveys have shown industry interest and general supportiveness of the scheme; however, they have also highlighted scepticisms. Reservations relate to its contribution to national biosecurity and the need for government backing, either through a compensation pot or by redefining government procurement strategies prioritising biosecurity, while adhering to equality principles (HTA, 2019). Recently, a paper by Dunn, Marzano and Forster (2019) examined the support of biosecure accredited plants by UK consumers, and thus the appetite for a Plant Health Assurance Scheme, a key determinant for the success of the industry scheme. Based on survey responses, they explore the necessary scope of such a scheme and outline ways to gain public appeal for healthier plants. Results show that public support for the scheme through purchasing habits is unlikely without raising awareness, high quality assurance and industry wide coverage.

1.3.3 Research gap and thesis aims

Despite the potential success of private public partnerships to manage pests through risk reduction, income stabilisation, coordination efforts, and information sharing from agents to governments, there are very few frameworks exploring the boundaries of private and public roles, and fewer still that aim to understand private agent motivations within these schemes. For example, while the previously identified case studies are often cited as exemplary schemes, both public and private agents have rarely been explicitly modelled to optimise the design of schemes that take into consideration each other's actions.

Within this context, the goal of this thesis is to explore the role of government in incentivising private biosecurity efforts within different forms of PPPs and illustrate how novel schemes can facilitate more effective pest management. The purpose of this thesis is threefold. The first objective is to provide a foundation on the role of private–public contracts as a novel instrument in plant pest and disease management to capture risk-sharing through to the contractual nature of PPPs. The second objective is to model cost sharing in a PPPs instrument, where the role of government support in incentivising private actions towards biosecurity is explored. The third objective is to understand stakeholders' preferences for a PPP which incorporates a cost sharing element within a risk sharing framework. Together, the work aims to inform the design of new contingent biosecurity PPPs to manage pests and diseases.

Developing and implementing effective management strategies is particularly challenging. Specifically, the complex nature of the industry means that plant related incursions exhibit substantial stakeholder heterogeneity while potential impacts on ecosystem services and human health have significant social characteristics (Donovan et al., 2013). Moreover, plant and tree pests often have a less immediate and visible effect but may have more profound impacts on the landscape in the long term (Boyd et al., 2013; Wilkinson et al., 2011; Mumford, 2011). It is important to note that while this study is motivated by a desire to control plant pests, the models and its implications may also generalise to animal health issues.

1.4 Breakdown of chapters

Pests management is an interdisciplinary field that requires understanding of the biological factors about the spread of the invasion as well as the economic, social, and political aspects that can influence management practices. As such, the development of models to support policy decision-making need to incorporate some of this complexity and, with this in mind, the analysis in this thesis borrows elements from different fields.

Chapter 2: Public–Private Partnerships for Biosecurity: An Opportunity for Risk Sharing

The goal of Chapter 2 is to provide a foundation for the role of PPPs for pest management by understanding how to structure contractual payments to provide risk-sharing benefits. In this chapter, I develop a theoretical framework to study private stakeholder motivation to establish PPPs that split the responsibilities of management between the public and private sector. In particular, it models how the government can create incentives for farmers to invest in biosecurity efforts and determines optimal payments to encourage biosecurity and cooperation between agents to share the risk of outbreaks. The work uses contract theory and, in particular, principal-agent modelling. In the last few decades, the principal-agent models have received attention as an important analytical method to study asymmetric information on the use of incentive schemes and contracts among agents. Their popularity is thus justified because often the objectives of the parties in the partnerships cannot be automatically aligned with each other. In principal-agent theory, the central concern is how the principal can best induce the agent to perform as the principal would prefer, taking into account the difficulties in monitoring the agent's activities. In particular, I will focus on contracts where private biosecurity effort is not verifiable. This set up is in line with the challenges present in pest management, when the government cannot monitor perfectly all the efforts that stakeholders have put in place to deal with outbreaks.

Chapter 3: The role of government in supporting voluntary biosecurity schemes

The next goal of the thesis is to provide a framework to explore cost-sharing within a PPP framework. Chapter 3 explores the government’s role in encouraging private biosecurity investments through private-public biosecurity schemes. The objective is to understand whether and how guaranteeing post-outbreak compensation payments to agents who join biosecurity schemes enhances the formation of self-enforcing stable biosecurity coalitions. The trade-offs between governmental expenditure on measures that reduce the general probability of an outbreak (e.g. pre-border security checks and inspections), and compensation payments to members for damages in the event of an outbreak, is also explored. This work informs the analysis of trade-offs faced by policy decision making when determining how to prioritise budgets for plant and animal health, and contributes more generally to the work on modelling contractual PPPs for biosecurity.

Chapter 4: Understanding stakeholder participation in public-private insurance schemes for pest management

The last objective of the thesis is to understand uptake of a public-private partnership scheme that incorporates both the cost and risk sharing elements previously explored. Using the case of subsidised crop insurance in Spain, in Chapter 4 I estimate crop producers' preferences for insurance as an instrument to manage risks from pests and diseases, while exploring novel cost sharing arrangements between the private and public sectors that may contribute to higher farmer engagement. In particular, I use a choice experiment to investigate the potential use of subsidised private-public insurance as an incentive policy to achieve higher biosecurity based on stakeholders' preferences for this instrument. Despite the fact that information about the potential demand for novel insurance products is crucial to develop attractive products to farmers, European empirical studies on this topic are rare (some exceptions are Mercadé, Gil José, Kallas & Serra et al., 2009 and Liesivaara & Myyrä, 2014). Previous literature on demand for crop insurance has mostly focused on farm characteristics as factors that may affect insurance purchases and less attention has been given to farmers' preferences for scheme characteristics (Mercadé et al., 2009). While the aim of this work is not to evaluate the supply and actuarial fairness of the insurance policies, the article provides a foundation to stimulate further contributions that explore farmer's preferences for different risk management policies.

Chapter 5: Discussion, policy implications and suggestions for future research

Lastly, Chapter 5 briefly reiterates the overall aim and approach and provide short summaries of the three papers that comprise the thesis. The concluding chapter also includes critical reflections on the methods and frameworks used and highlights the policy impact, the overall contributions to knowledge offered by this thesis and the novelty of the research. The chapter concludes with a discussion of opportunities for future research.

1.5 References

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Chapter 2 - Public-private partnerships for biosecurity: an opportunity for risk sharing

2.1 Preface

A key component of a successful public-private partnership is clear definition of prevention and control responsibilities among all stakeholders involved. The use of contracts can help establish a successful ex ante mechanism by explicitly signalling who must bear the risks and responsibilities of biosecurity management measures. With this in mind, I set out to achieve my first research objective, which was to develop a parsimonious framework to gain an understanding of how and whether contingent contracts and payments could encourage responsibility and risk-sharing.

Principal-agent models deal with the challenges that arise under incomplete and asymmetric information, when a principal delegates work to an agent. In a plant biosecurity scenario, these conflicting interests appear between the government (the principal), which is concerned with public benefits, and the private agents (for example farmers or land managers), who are motivated by their own private benefits. In this setting, the government must construct means by which private agents act on their own interest to carry the agreed level of biosecurity efforts but must overcome the additional challenge that it cannot verify whether the private agents have behaved appropriately.

Borrowing from this literature of contract theory, in this Chapter I develop a principal-agent model of two private agents, for example farmers or landowners, conducting biosecurity efforts while receiving compensation payments for their biosecurity actions. I focus on a particular case where, due to the heterogeneity of stakeholder interests and the significant social character of the potential impacts on ecosystem services and human health, an agreement is reached by placing the cost contribution on the government side.

This Chapter shows that behind the concept of PPPs there is a strong gain on risk minimisation facilitated by this public-private contractual scheme by making payments to agents which depend on both their performance and that of the other stakeholders. Moreover, I find that the optimal level of payment depends on the individual agent's capacity of deriving private benefits from healthier plants. Lastly, the work also demonstrates the usefulness of principal-agent models for conceptualising contracting problems in biosecurity, with an aim to encourage further discussions on establishing statutory responsibility among a set of stakeholders for improved plant health.

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Declaration: I declare that the work submitted is my own. The contribution of the co-author is as follows:

Dr. Julia Touza and Dr. Jon Pitchford: Supervision, review and editing.

PUBLIC–PRIVATE PARTNERSHIPS FOR BIOSECURITY: AN OPPORTUNITY FOR RISK SHARING

2.2 Abstract

Private efforts to prevent and control biological pests and infectious diseases can be a public good, and so incentivising private biosecurity management actions is both desirable and problematic. Compensation contracts can encourage biosecurity efforts, provide support against the collapse of economic sectors, and create an insurance network. We conceptualise a novel biosecurity instrument relying on formal compensation private–public partnerships using contract theory. Our framework explains how the public sector can harness increased private biosecurity measures by making payments to agents which depend both on their performance and that of the other stakeholders. Doing so allows the government to spread the risk across signatory agents. The framework also improves our understanding of government involvement due to public effects of biosecurity, influenced by the private agents' capacity to derive private benefit from their own efforts on monitoring and control. Lastly, these theoretical results provide a foundation for further study of contractual responsibility sharing for pest management.

2.3 Introduction

The number of plant and animal disease and pest outbreaks is increasing rapidly as a consequence of globalisation of trade and travel. Developing efficient management plans for prevention and control is of key importance to avoid economic, environmental and human health impacts (Bebber, et al., 2014; Dalmazzone & Giaccaria, 2014; Donovan et al., 2013; Simberloff, 2012). However, designing and implementing reliable biosecurity policies is a difficult challenge, and this has led to an increasing literature on the subject in the last decade (for a review see Epanchin-Niell, 2017; Horan & Lupi, 2010; Keller et al., 2011; Lodge et al., 2016).

In economic terminology, policies to manage pests have public good characteristics (Perrings, 2005; Perrings et al., 2002). In particular, biosecurity efforts are an impure public good, meaning that agents benefit from their own biosecurity efforts as well as those of others (Sandler & Arce, 2002), making it challenging to encourage private biosecurity efforts. The difficulty in management arises because agents have incentives to invest in their own direct benefits but not to take into consideration the contribution to the others (Perrings, 2016). In addition, pest management is influenced by many heterogeneous public and private actors, including farmers, landowners, managers, agribusiness, conservation agencies and local management authorities. Each stakeholder has different preferences for management practices and acceptable risks of outbreaks (e.g. García-Llorente et al., 2008; Humair et al., 2014; Mills et al., 2011; Reed & Curzon, 2015). Agreeing a set of actions towards the control of an outbreak with such heterogeneity of agents is challenging (e.g. Liu et al., 2012; Marzano et al., 2015) and often results in delayed responses and poorly coordinated policies due to incentives to free ride on the control efforts of others (Cook, et al., 2010; Mumford, 2011).

Economic factors justifying government intervention in pest management include public good characteristics, coordination challenges and information failures, as well as other national interests such as income distribution or industry resilience (Epanchin-Niell, 2017; Perrings et al., 2002; Ramsay et al., 1999). The government has a series of instruments available, including providing economic incentives (i.e. subsidies or taxes), command and control policies (i.e. bans or fines), and also voluntary measures (i.e. codes of conduct). However, a framework for biosecurity needs to be carefully designed to promote private efforts, cooperative behaviour and risk sharing (OECD, 2011a). To establish a successful *ex-ante* mechanism to improve plant health it is crucial that agents receive clear signals on who must bear the risks and responsibilities of coping with an outbreak (Bremmer & Slobbe, 2011; OECD, 2011b).

We focus on the use of private–public partnerships (PPPs) for pest management, in which both the government and industry partners agree on a common management strategy. Even though there is large a variety of biosecurity agreements, from full government support (such as the management of Canadian Beavers in Argentina (GEF project 2012–2016)) to industry-based schemes (such as the Dutch Potatopol Scheme[2]), this paper is motivated by cost and responsibility sharing schemes. Cost and responsibility sharing agreements are relatively new policies which divide the obligations for action and damage control between the public and private sector through a predetermined agreed level, while encouraging investment in biosecurity measures. They have recently been applied in a plant and animal health context in Australia[3] (Plant Health Australia, 2014; Australian Animal Health Council, 2016).

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[2] Potatopol. Potatopol. (2010) http://www.potatopol.nl.

[3] The Australian Emergency Plant Pest Response Deed (EPPRD) is currently the most detailed contingent cost sharing initiative for plant and tree health, including a combination of agreements on private actions to prevent and respond incursions and the legal commitment to follow these plans if an outbreak occurs (Anderson, 2005; Cook et al., 2010; Mumford, 2011). The scheme describes the rules on splitting the costs between the public and the private sector depending on the potential damage due to pests.

It has been argued that PPPs for biosecurity encourage a consistent and coordinated management approach that can reduce costs in the long run, achieving economies of scale and developing combined strategies that otherwise would not be possible (Cook et al., 2010; Krauss & Duffy, 2010; Mumford, 2002, 2011; Waage et al., 2005). PPPs have the potential additional benefit of being a pre-agreed policy before an outbreak occurs, thereby reducing the response time and minimising the size and impact of the incursion (Heikkilä & Peltola, 2004; Kaiser & Burnett, 2010; Leung et al., 2014; Sims & Finnoff, 2013). Moreover, cooperation between government and the private sector has been shown to be essential to ensure a quick control and eradication of outbreaks (van Asseldonk & Bergevoet, 2014).

The development of these partnerships involves deciding how to split both the costs and responsibilities between the state and private partners. We concentrate on responsibility-sharing, due to its importance in establishing statutory responsibility among a set of stakeholders to develop coordinated actions to prevent and control an outbreak. We focus on a general case when, due to the heterogeneity of stakeholder interests and the significant social character of the potential impacts on ecosystem services and human health (e.g. Donovan et al., 2013), an agreement is reached by placing the cost contribution on the government side (Waage et al., 2007).

This situation is particularly common in plant pests since their effects may be less immediate and visible but may have more profound impacts on the landscape in the long term (Waage & Mumford, 2008; Wilkinson et al., 2011). Due to these challenges, compensation for breaches in plant health is much less common (Mumford, 2011). While this study is motivated by a desire to control plant pests, the model and its implications may also generalise to certain animal pests.

Our goal is to understand whether and how contracts offering contingent compensation payments from the government can spread the risks of an outbreak across signatory agents. We develop a contract theory model of two private agents, for example farmers or landowners, conducting biosecurity efforts while receiving compensation payments for their actions. Given the impure public good character of agents' biosecurity actions (Reeling & Horan, 2017) we also explore the implications on the level of payments when agents can partly appropriate the benefits from their own biosecurity efforts.

We focus on plant health as a proxy measure for the level of pest or disease infestation in crops and trees. Plant health outcomes, however, depend on other factors than the biosecurity measures of the agents. We include an external independent random shock representing uncontrollable factors that affect the pest damage, such as the effect of weather on pathogen spread and life-cycle (Guernier et al., 2004; Whittaker et al., 2001) or the impact of different management practices throughout the supply chain (Dehnen-Schmutz et al., 2010; Hulme et al., 2018). We allow for neighbourhood effects via a correlation parameter.

The paper is structured as follows. The next section introduces the components of the theoretical framework. Results are developed in section 2.3. The analytical results are complemented with numerical simulations in section 2.4 to further explore the importance of the agent’s capacity to derive private benefit from his own biosecurity efforts (public goods vs. impure public goods) on payments and overall plant health achieved by the scheme. The theoretical findings are placed into a more applied context in the Discussion and Conclusion sections.

2.4 The PPP compensation model

The development of a PPP to create a system of contingent payments for biosecurity efforts can be modelled as a contract theory problem: statutory responsibility for pest management is assigned to the private agents and, in exchange, they receive compensation from the government (the principal). We expand the traditional principal-agent model to account for two agents who receive funds based on the health of both of their resources, similar to the model by Itoh (1991) and the later adaptation by Bolton and Dewatripont (2005).

Principal-agent models deal with the challenges that arise under incomplete and asymmetric information, when a principal delegates work to an agent. In a plant biosecurity scenario, these conflicting interests appear between the government, which cares about public benefits, and the private agents, who are concerned about net economic benefits. Public benefits include avoiding threats to food production, preventing the collapse of agricultural or ornamental sectors due to extensive pest damage, avoiding the destruction of large areas of woodlands, planted forests or urban parks which could impact vital forest ecosystem functions such as air quality regulation, cause severe indirect economic losses to property values, affect recreational opportunities, and reduce human health and well-being (e.g. Jones, 2016; Kondo et al., 2017; Kovacs et al., 2011; Pennisi, 2010).

However, the government often cannot easily verify that the private agents have behaved appropriately (Eisenhardt, 1989). Compensation payments are modelled here to be contingent on the final quality of health of the plant or crops, rather than the actual private costs and measures in biosecurity efforts. Experience with payments for ecosystem services shows that results-based payments are more appropriate when it is less costly to monitor outcomes rather than efforts and when there is higher uncertainty on the effectiveness of efforts to achieve the outcome (Börner et al., 2017; Engel et al., 2016; White & Hanley, 2016). An additional benefit of adopting outcome-based compensation is that such schemes have been shown to be effective in encouraging agents to use private information to generate outputs, in comparison to payments for actions (Bolton & Dewatripont, 2005; Hanley et al., 2012; White & Hanley, 2016). Moreover, compensating for outcomes may also decrease the risk for moral hazard (Börner et al., 2017). However, we note that that some biosecurity PPPs, such as Recognised Biosecurity Groups in Western Australia[4], have compensation programmes set up in a different format: in this case a dollar-for-dollar arrangement whereby government contributions are determined by the amount of effort invested by private providers (this option received more support from landholders throughout a consultation process[5])

Public–private contractual schemes need to satisfy both participation and incentive compatibility constraints. The participation constraint requires that the agent must be at least as well off by contracting as he would be on his own. The incentive compatibility constraint ensures that the agent is behaving according to his own incentives, since an agent's biosecurity efforts are not directly observable by the government, and yet is encouraged to adopt an optimal level of biosecurity. The components of the model are described below.

2.4.1 The agents

We consider two independent, identical[6], and representative agents, labelled by subscripts 1 and 2, each in charge of producing healthy plants by conducting biosecurity efforts in monetary terms, a_i, such as sanitation felling or usage of pesticides and fungicides. However, plant health is also subject to external uncontrollable random factors described by a random shock ξ_i, such as damages caused by climatic events. This random effect takes into consideration the fact that plant health is dependent on factors beyond the control of agents. Moreover we allow for neighbouring effects through the inclusion of a correlation parameter α: if $\alpha \neq 0$ then the health state of the plants of an agent not only depends on his investment in biosecurity efforts and his random external effects, but also on the external factors affecting the other agent. The concept of 'neighbouring effects' is not limited to spatially adjacent agents, and could encompass more general geographic or socioeconomic interconnections. We represent the health quality q_i of agent i's plants and trees as follows, measured in monetary terms:

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[4] Agric.wa.gov.au (2017). Recognised Biosecurity Groups (RBGs). https://www.agric.wa.gov.au/bam/recognised-biosecurity-groups

[5] We would like to thank an anonymous referee for bringing our attention to the way in which PPPs for biosecurity are forming in Western Australia.

[6] Agents are assumed to be identical for simplicity purposes. However this assumption could be relaxed in future work.

$$q_i = a_i + \xi_i + \alpha\, \xi_j . \qquad (1)$$

For simplicity, we assume that each $\xi_i \sim N(0, \sigma^2)$ i.e. they are independently and normally distributed external effects[7], and we note that these local random effects may be beneficial or detrimental in any given year.

There are, of course, other possible ways to formulate the problem which would depend on the details of the outbreaks and control measures, for example having the neighbouring spillover effect depend on the plant health of the neighbouring farm.[8] The independent nature of the random factor, as specified in equation (1), captures the complexity and unpredictability of ecological and climatic effects on plant health.

The government compensates each agent for the health quality of their plants with a payment of w_i. We assume that an agent is able to retain part of the benefits derived from producing healthy plants and trees, so that private agents are capable of appropriating part of their own biosecurity benefits. Agents are risk averse on profits and we further assume that they have an exponential utility[9] which depends on the cost $\phi_i(a_i)$ of their chosen level of biosecurity efforts, the compensations they receive, and their capacity to appropriate biosecurity benefits. This allows the utility for agent *i* profits from receiving payment w_i for biosecurity efforts a_i to be written as follows:

$$u_i(w_i, a_i) = -e^{-\eta_i [w_i + \delta_i\, q_i\, - \phi_i(a_i)]} \qquad (2)$$

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[7] Assuming that the shocks are independent and normally distributed also enables us to derive an analytical solution when solving the optimisation problem due to the properties of the exponential distribution.

[8] For example, an alternative formulation is $q_i = a_i + \xi_i + \alpha q_j$, which captures a stronger interaction between the agents' plant health outcomes. This does not affect the main qualitative results, which become:

$$a_i = \frac{v_i + \delta_i + \alpha h_i}{c_i(1-\alpha^2)};\ v_1 = -\frac{\delta_i + 1}{(\alpha^2 - 1)(c_i \eta_i \sigma^2 + 1)} - \delta_i\ ;\ h_1 = \frac{\alpha(\delta + 1)}{(\alpha^2 - 1)(c_i \eta_i \sigma^2 + 1)}.$$

We thank an anonymous referee for suggesting this alternative specification.

[9] Exponential utility was chosen because it has constant absolute risk aversion and it is possible to capture all the relevant information about an agent's risk preferences with a single parameter, the coefficient of risk aversion. Moreover, the exponential utility form allows analytical solutions. These benefits make it a commonly used functional form and it is often used in contract theory (for example Bolton and Dewatripont, 2005). The main results do not change with other functional forms that have constant absolute risk aversion.

where the coefficient η_i represents the degree of risk aversion, and δ_i is the coefficient of appropriation of private biosecurity benefits. Finally, we assume that the costs of control are quadratically[10] related to the surveillance and control levels applied, meaning that costs increase with additional efforts. This property is common in pollution or biosecurity problems, since efforts become increasingly difficult and costly.

$$\phi_i(a_i) = \frac{1}{2} c_i a_i^2 \qquad (3)$$

were c_i are the marginal costs incurred by the agents for their biosecurity efforts.

2.4.2 The government

We assume that the government is willing to take more risks than the producers, and is risk neutral. We can express the utility of the government measured in monetary units as:

$$U = \mathbb{E}\left[\sum_{i=1}^{2} (q_i - w_i)\right]. \qquad (4)$$

2.4.3 The payments

Following contract theory, models of performance-based payments typically consist of two parts: a fixed payment and a variable incentive payment (Bolton & Dewatripont, 2005). To model agreement formation, we assume that the payments not only depend on the agent's own output, but also on the neighbouring agent's health state, so compensation payments depend on all the agents' actions (Bolton & Dewatripont, 2005). The government's linear incentive scheme in monetary terms is:

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[10] Using a quadratic function also ensures that the optimisation problem has an interior solution due to its convex and smooth nature.

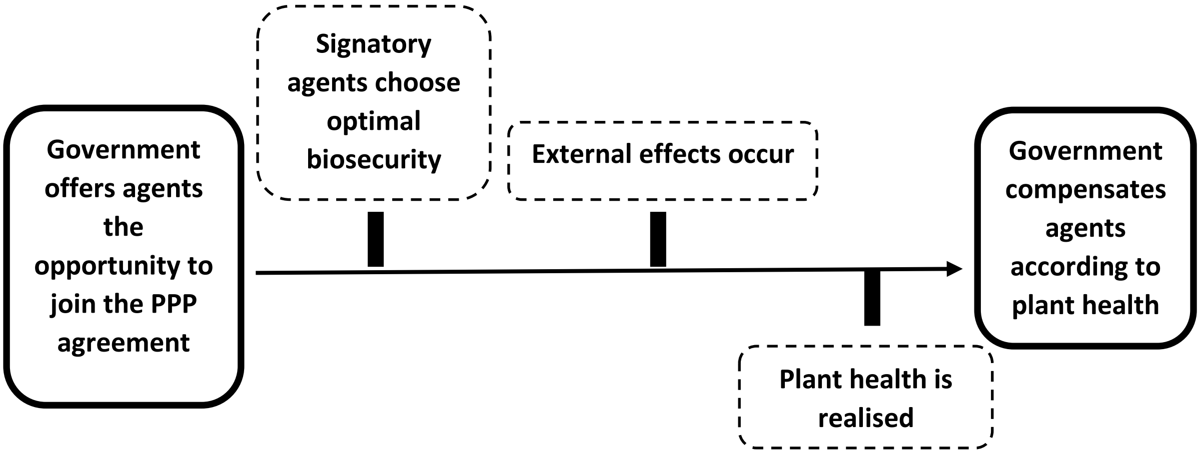
$$w_i = z_i + v_i q_i + h_i q_j \qquad (5)$$

where z_i is a fixed compensation amount to each of the agents, v_i is the marginal compensation depending on their health state, and h_i is the marginal compensation from the neighbour's plant health, which could encourage mutual agreements between the agents. If the payments from the government are not dependent on the performance of the other agent, then $h_i q_j = 0$.

2.4.4 The government's management problem

First, the government offers the agents an opportunity to join the partnership. Agents that agree to contract with the government then decide their optimal investment in biosecurity to maximise their own expected utility. Uncontrollable effects then occur that affect plant health and the occurrence of pest damages. Plant health quality is realised by both agents and the government, and agents receive the payment based on the quality of the plants on their land.

Figure 2.1 Annual timeline of events



If we assume symmetry, so that both agents are equal in costs, risk aversion and private benefit appropriation capacity, then the problem is simplified and solves for only one optimal scheme $\{a_i, w_i\}$. Thus, the government maximises its expected utility of profits in relation to agent 1 by solving:

$$\max_{\{a_1, z_1, v_1, u_1\}} \mathbb{E}\left[q_1 - w_1\right] \qquad (6)$$

subject to:

$$\mathbb{E}\left[-e^{-\eta_1\left[w_1 + \delta_1 q_1 - \phi_1(a_1)\right]}\right] \geq u(\overline{w}) \qquad (7)$$

and

$$a_1 \in \arg\max_{\{a\}} \mathbb{E}\left[-e^{-\eta_1\left[w_1 + \delta_1 q_1 - \phi_1(a_1)\right]}\right]. \qquad (8)$$

That is, the government maximises expected utility subject to the participation (equation (7)) and incentive compatibility constraints (equation (8)) of the representative agent. $u(\overline{w})$ represents the utility of profits associated with the option of not participating in the scheme. We set $u\ (\overline{w}) = \gamma$, and note that $\gamma < 0$.

The problem can be transformed into an unconstrained optimisation problem.[11] The first step is to solve the agent's maximisation problem (the incentive compatibility constraint) to obtain the agent's optimal biosecurity efforts, a_1, taking payments as given. Using the properties of the lognormal distribution and after some algebra, each agent's utility maximisation problem becomes:

$$\max_{\{a_1\}} \left\{z_1 + v_1 a_1 + h_1 a_2 + \delta_1 a_1 - \frac{1}{2} c_1 a_1^2 - \frac{1}{2} \eta_1 \sigma^2 \left[(v_1 + h_1 \alpha + \delta_1)^2 + (h_1 + v_1 \alpha + \delta_1 \alpha)^2\right]\right\} \quad (9)$$

The agent's optimal biosecurity efforts are given by the first order condition:

$$a_1 = \frac{v_1 + \delta_1}{c_1}. \qquad (10)$$

Thus, the agent's own optimal biosecurity efforts are determined by the ratio of the marginal payment and capacity of appropriation of public benefits, to the marginal costs of biosecurity efforts.

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[11] In the Appendix, we include the detailed step-by-step process of solving the problem of the government.

The government's problem can be represented by substituting the first order condition from the agent's optimisation problem and the participation constraint into the objective function of the government (equation (6)) transforming the problem of the government to:

$$\max_{\{v_1,u_1\}} \left(\frac{v_1+\delta_1}{c_1}(1+\delta_1) - \frac{1}{2}c_1\left(\frac{v_1+\delta_1}{c_1}\right)^2 - \frac{1}{2}\eta_1\sigma^2[(v_1+h_1\alpha+\delta_1)^2+(h_1+v_1\alpha+\delta_1\alpha)^2] - \gamma \right) \quad (11)$$

The optimal marginal payments, h_1 and v_1, are derived from the first order conditions of the problem of the government. For a given v_1, h_1 is determined to minimise the risk (third and fourth term of equation (11)) and then v_1 is set optimally to trade off risk sharing and incentives:

$$h_1 = -\left(\frac{2\alpha(\delta_1+1\,)}{1+\alpha^2+c_1\eta_1\sigma^2(1-\alpha^2)^2}\right). \qquad (12)$$

$$v_1 = \frac{(1+\alpha^2)(\delta_1+1)}{1+\alpha^2+c_1\eta_1\sigma^2(1-\alpha^2)^2} - \delta_1. \qquad (13)$$

The results for the marginal payments capture the core motivation behind the use of contracts for biosecurity efforts: risk sharing. The marginal payment for the neighbour's plant quality, h_1, is negative (assuming the correlation is positive, $\alpha > 0$), implying that an agent is disadvantaged by the neighbouring agent's more healthy plants. By introducing payments that depend on both agents' outputs, the government filters the common shocks and thus reduces each agent's exposure to risk.

Moreover, the incapacity of the government to fully observe the biosecurity efforts implemented by the agents, and the uncertainty of their outcomes as represented by the external random shocks ξ_i , causes a distortion in the solution and a first-best solution is not achieved (Bolton & Dewatripont, 2005). This can be seen in the optimal marginal payments (equations (12) and (13)), in the term $c_1\eta_1\sigma^2(1-\alpha^2)^2$, which captures the frictions of asymmetric information between the private agents and the government.

The government uses z_1, the fixed part of the payments, to ensure that the contract is appealing to the agents (equation (14)); that is z_1 becomes the residual of the incentive participation constraint (equation (7)). The fixed payment is then set so that the private benefits derived by the agent from joining the contract cover the baseline utility of profits and are equal to the costs, including the personal costs of conducting biosecurity effort as well as the disutility of the contract from the uncertainty of plant health due to the agent's risk aversion:

$$z_1 = \left(\frac{1}{2}\right)\frac{(1+\alpha^2)(\delta_1+1)^2\left(\alpha^4 c_1\eta_1\sigma^2 + \left(-2c_1\eta_1\sigma^2 - 1\right)\alpha^2 + 4\alpha + c_1\eta_1\sigma^2 - 1\right)}{c_1\left(1+\alpha^2+c_1\eta_1\sigma^2(1-\alpha^2)^2\right)^2} + \gamma. \quad (14)$$

2.5 Implications of the optimal PPP solution

The expected final health quality of the plants (equation (15)) is given by the optimal level of biosecurity efforts employed by the private agents:

$$\mathbb{E}\left[q_i\right] = \frac{(1+\alpha^2)(\delta_i+1)}{c_i\left(1+\alpha^2+c_i\eta_i\sigma^2(1-\alpha^2)^2\right)}. \quad (15)$$

Total expected compensating payments from the government to the agent are given by:

$$\mathbb{E}[w_i] = \frac{-(1+\alpha^2)\left(\delta_i^2 - 1\right)}{c_i\left(1+\alpha^2+c_i\eta_i\sigma^2(1-\alpha^2)^2\right)} + \gamma. \quad (16)$$

As the agents appropriate higher benefits from the impure public good nature of their biosecurity efforts, total expected payments decrease. If $\delta_i = 1$ (i.e. if the public element of investing in biosecurity efforts is minimal) then there is no need for the government to create positive incentives, so total expected payments are zero.

The expected utility of the government from setting the contracts is given by the expected net benefits of plant health quality and the costs of payment compensation:

$$\mathbb{E}\left[q_1 - w_1 + q_2 - w_2\right] = \frac{(1+\alpha^2)(\delta_i + 1)^2}{c_i\left(1 + \alpha^2 + c_i\eta_i\sigma^2(1-\alpha^2)^2\right)} - \gamma. \qquad (17)$$

The expected utility gain (over no contract) of the agents is the baseline utility of profits, γ, since the government adjusts the fixed payment component to just meet the participation constraint thus avoid paying excess rent:

$$\begin{aligned} &\mathbb{E}\left[-e^{-\eta_i[w_i + \delta_i\, q_i - \phi_i(a_i)]}\right] \\ &= z_i + v_i a_i + h_i a_j + \delta_i a_i - \frac{1}{2}c_i a_i^2 \\ &- \frac{1}{2}\eta_i\sigma^2[(v_i + h_i\alpha + \delta_i)^2 + (h_i + v_i\alpha + \delta_i\alpha)^2] = \gamma. \end{aligned} \qquad (18)$$

2.5.1 Sensitivity to model parameters

The exercise was conducted by looking at effects of a marginal increase in each of the parameters on the optimal variables and expected values (equations (10), (12)–(17)) while keeping all other things constant. Throughout this analysis we have assumed that external random effects on health quality are positively correlated across agents. The results are summarised in Table 2.1.

Table 2.1 Sensitivity analysis of model parameters on payments, utility, plant health and biosecurity efforts

	Marginal cost	**Risk aversion**	**Variance of external effects**
Private biosecurity efforts	$\frac{\partial a_i}{\partial c_i} < 0$	$\frac{\partial a_i}{\partial \eta_i} < 0$	$\frac{\partial a_i}{\partial \sigma^2} < 0$
Marginal payment for own quality of plant health	$\frac{\partial v_i}{\partial c_i} < 0$	$\frac{\partial v_i}{\partial \eta_i} < 0$	$\frac{\partial v_i}{\partial \sigma^2} < 0$
Marginal payment for neighbour's quality of plant health	$\frac{\partial h_i}{\partial c_i} > 0$	$\frac{\partial h_i}{\partial \eta_i} > 0$	$\frac{\partial h_i}{\partial \sigma^2} > 0$
Expected fixed payment	$\frac{\partial \mathbb{E}[z_i]}{\partial c_i} < 0$	$\frac{\partial \mathbb{E}[z_i]}{\partial \eta_i} < 0$	$\frac{\partial \mathbb{E}[z_i]}{\partial \sigma^2} < 0$
Expected plant health	$\frac{\partial \mathbb{E}\left[q_i\right]}{\partial c_i} < 0$	$\frac{\partial \mathbb{E}\left[q_i\right]}{\partial \eta_i} < 0$	$\frac{\partial \mathbb{E}\left[q_i\right]}{\partial \sigma^2} < 0$

Expected total payments	$\frac{\partial \mathbb{E}[w_i]}{\partial c_i} < 0$	$\frac{\partial \mathbb{E}[w_i]}{\partial \eta_i} > 0$	$\frac{\partial \mathbb{E}[w_i]}{\partial \sigma^2} > 0$
Expected government utility	$\frac{\partial \mathbb{E}[U]}{\partial c_i} < 0$	$\frac{\partial \mathbb{E}[U]}{\partial \eta_i} < 0$	$\frac{\partial \mathbb{E}[U]}{\partial \sigma^2} < 0$

Increases in marginal cost decrease the level of biosecurity efforts chosen by the agents, as well as the agent's own marginal payments. The effect on the agent is in part counteracted by an increased marginal payment received from the neighbour's plant health quality. However, total expected payments will decrease since, overall, private agents would invest less in biosecurity efforts with increased costs. Overall expected plant health and government utility is lower.

As risk aversion increases the agent receives higher compensation for his own plant quality, and lower for the neighbour's health outcome. With more risk aversion, agents are less inclined to participate in the contract agreement and to invest in biosecurity efforts due to the uncertainty in health outcome. Expected plant health is lower. Therefore, total payments need to increase, but this comes at the expense of lower government utility. In the extreme case where both agents and the government are risk neutral, $\eta_i = 0$, the contract induces first-best biosecurity efforts and full compensation, $v_i = 1$.

Higher variance of the external random effects lowers biosecurity efforts by the agents, and the government decreases the marginal payment for the agent's own plant health, while the marginal payment for the neighbour's plant health increases. The fixed component of the payment is also reduced, but the agent's total payments increase to compensate for the increase in uncertainty. Overall plant health is lower, as is government utility, in this case.

2.5.2 The importance of private appropriation of benefits

A special case occurs when the government might want to encourage good health, but the agents do not derive utility from that improved health state. For example, a landowner may overlook the benefits of pre-emptive harvesting of a forest parcel in a landscape in response to a potential pest outbreak that could spread to a neighbouring forest (Kizlinski et al., 2002). In such a case, biosecurity efforts are a case of pure public goods. Assuming that private agents are not altruistic, they need monetary incentives to invest in biosecurity to ensure pest free plants and trees since benefits to society from healthy plants are not sufficient to justify private biosecurity actions. In such a case we can look at the specific scenario when the agent's income is dependent only on the payments and cost of biosecurity levels ($\delta_i = 0$).

Under this scenario, optimal biosecurity efforts, marginal payments and expected values of plant health and utility of dealing with impure public goods versus pure public goods are summarised in Table 2.2. To compare both scenarios, we describe the relative change calculated as the expected value with impure public goods, minus the case for pure public goods, divided by the pure public good case.

Table 2.2 Comparison of biosecurity efforts, payments, and utility for the case of impure public goods (both private and public appropriation of private biosecurity benefits from healthier plants) vs. pure public goods (only public benefits)

		Relative change	**Effects of impure public good cases**
Private biosecurity efforts	$\boldsymbol{a_i}$	δ	Biosecurity efforts increase with the capacity of private agents to appropriate personal benefits.
Marginal payment for own quality of plant health	$\boldsymbol{v_i}$	$-\frac{\sigma^2\eta\delta c(\alpha^2-1)^2}{\alpha^2+1}$	Own marginal payments are lower.
Marginal payment for neighbour's quality of plant health	$\boldsymbol{h_i}$	δ	Higher payments for neighbour contributions are necessary if the agent can appropriate part of the benefits.
Expected fixed payment	$\mathbb{E}[\boldsymbol{z_i}]$	$\delta^2+2\delta$	Higher fixed payments
Expected plant health	$\mathbb{E}[\boldsymbol{q_i}]$	δ	As a result of having private invested interests, plant health quality increases.
Expected total payments	$\mathbb{E}[\boldsymbol{w_i}]$	$-\delta^2$	Lower expected total payments to agents.
Expected private agent utility	$\mathbb{E}[\boldsymbol{UTIL_i}]$	0	Agent's utility does not change.
Expected government utility	$\mathbb{E}[\boldsymbol{U}]$	$\delta^2+2\delta$	Higher government expected utility, since the health outcome is superior and payments are lower with appropriation of private biosecurity benefits.

2.6 Numerical Illustration

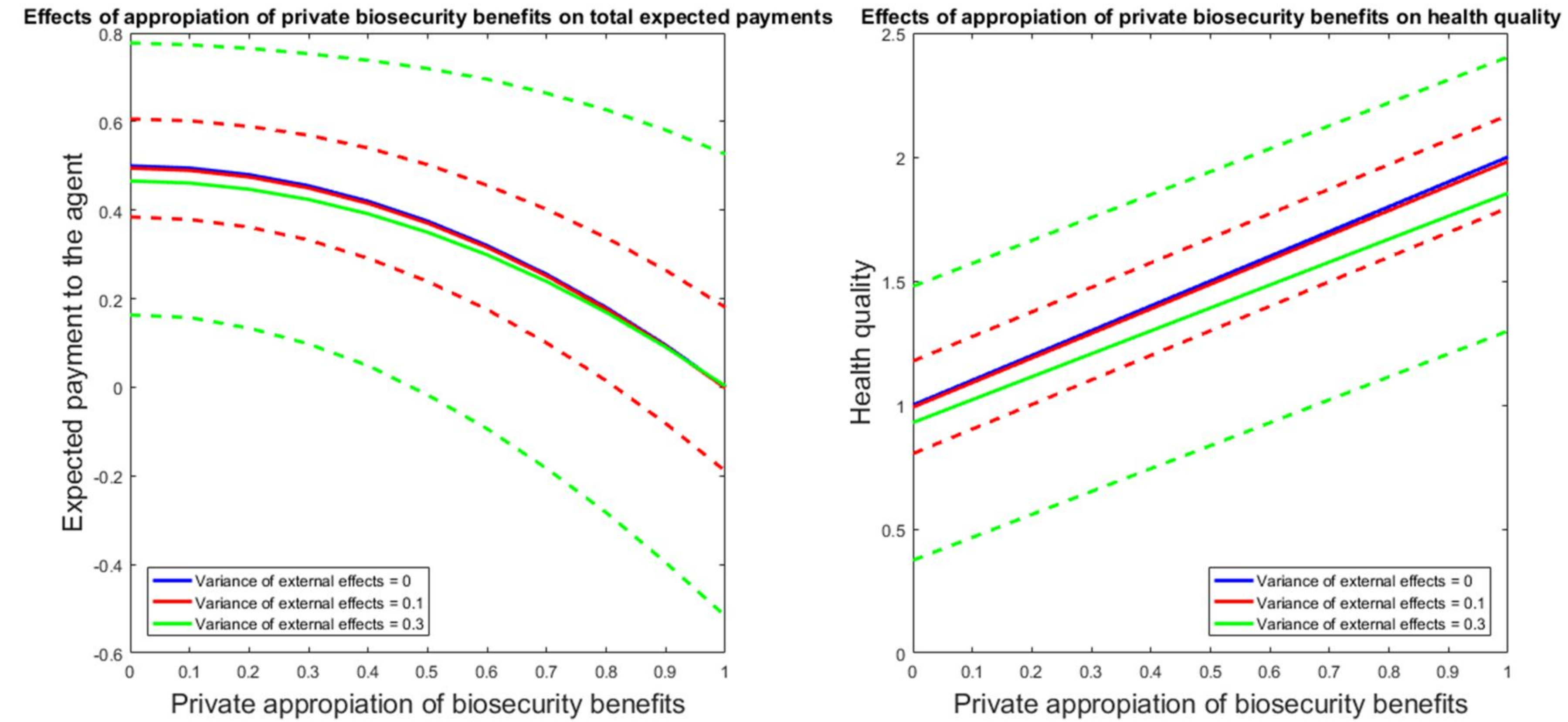
A numerical simulation illustrates the effects of different levels of appropriation of private biosecurity benefits on total payments received by the agent and final plant health quality achieved with the PPP scheme. Representative parameter values (Table 3) are given to the marginal cost of biosecurity efforts, the degree of risk aversion, and correlation of external shocks. Random shocks were simulated 100,000 times, and total expected payments and crop health quality were plotted for different levels of private appropriation of biosecurity benefits (between 0 and 1). Final expected values were obtained by averaging the results of the simulations for each appropriation capacity level. The mean and 5th and 95th quantiles of payments and plant health for each level of appropriation are displayed in Figure 2.1. This exercise was run for three different levels of variance of external effects.

Table 2.3 Parameter values used in numerical simulation

Correlation of neighbouring effects	α	0.5
Mean of normally distributed external effects	μ	0
Variance of normally distributed external effects	σ^2	0, 0.1, and 0.3
Marginal costs of biosecurity efforts incurred by the agent	c	1
Coefficient of risk aversion	η	2
Coefficient of appropriation of private biosecurity benefits	δ	From 0 to 1

The plot on the left in Figure 2.1 shows expected payments received by the agent for different levels of private appropriation of biosecurity efforts. Under no uncertainty, expected payments never exceed 0.5 (representing the shared risk between the government and the agents), and are never negative. As the external uncertainty increases, for high values of appropriation, total expected payments can become negative under some realisations. In this case of very impure public goods, private agents gain larger benefits from their mandated biosecurity efforts, and thus compensation payments are not necessary to provide incentives to invest in biosecurity efforts. The plot on the right in Figure 2.1 shows the effects of appropriation on plant health. With more impure biosecurity efforts (higher appropriation of benefits), better plant health is achieved, since agents also have private incentives to invest in biosecurity besides receiving government compensation payments. While expected payments decrease with appropriation at an increasing rate, plant health increases proportionally.

Figure 2.2 Expected payments and plant health for different degrees of private appropriation of biosecurity benefits by agents, and levels of variance of external shocks (Simulation mean and 5% and 95% quantiles reported).



2.7 Discussion: the social benefits of biosecurity partnerships

Our analytical model is intended to identify the key characteristics of cases when the benefits of biosecurity have a strong public component, which implies government support to provide greater resilience to private agents and industries. Our intention is not to mimic real world partnerships, but to provide clarity about the interactions between the government and private agents, achieved using a parsimonious and stylised model that captures the most important generalisable interactions underlying contractual relationships. Engaging all stakeholders is particularly critical in plant health, where the challenges are higher because fewer insurance policies or compensation schemes are available and market failures are more prevalent (Mumford, 2011). While the role of the government could also be remodelled to fit an industry funding scheme (e.g. Barbier & Knowler, 2006; or Fraser, 2018), we instead focus on the social desirability of the compensation payment.

We show that, in principle, the risk minimisation and risk sharing benefits of PPPs can be facilitated through a contract's coordinated approach. Our analytical model shows that the role of payments to encourage biosecurity efforts increases with decreased private appropriation capacity of benefits, which is consistent with Reeling and Horan (2015) who show that the coordination among agents depends on the relative endogeneity of risk, defined as the level at which private agents can take control of their own biosecurity risk.

Our analysis most closely relates to the work of Hennessy and Wolf (2015), who explore how information problems and externalities affect biosecurity incentives. However, their analysis is specific to livestock diseases and the implications of different externalities on disease management. Our emphasis is on engaging all stakeholders in the design of the optimal contract, which allows us to build a mechanism of payments that shares the risk among all agents. It is also important to note that principal-agent models have also been applied in a similar context for payments for ecosystem services (e.g. Engel et al., 2008; Ferraro, 2008; Hanley et al., 2012; Zabel & Roe, 2009).

However, there are two important caveats to our analysis. Firstly, we only consider complete contracts, an approach that has dominated the literature of asymmetric information (Wu, 2014). Our agreed contract directs all conditions of the contract under all contingencies, and is fully enforceable, i.e. is completely state contingent, unlike the real world. Thus, we have overlooked the role of contract enforcement and inspections of plant health. We refer the reader to other literature exploring this issue in detail, for example Gramig et al. (2009) and Jin and McCarl (2006). Despite evidence of inspection costs being substantial (Surkov et al., 2009; White and Hanley, 2016), new technology such as remote sensing and monitoring has the potential to make this process easier and less expensive.

Secondly, the potential emergence of moral hazard behaviour due to compensation (Bremmer & Slobbe, 2011) deserves consideration. Future research which could explore further the potential for minimising the risks of moral hazards is PPPs with cost and responsibility sharing, where the costs of prevention and control are shared between the government and the industry (OECD, 2011a). If these costs are split among all stakeholders, private agents may be less inclined to engage in moral hazard.

There is a need for future work to explore how to design a network of PPPs, where crucial information is shared, and biosecurity efforts are aligned towards an agreed biosecurity objective to monitor the broader system being managed. Coordinating such a network of PPPs to achieve a broader health quality goal is a major challenge. Of special importance will be the nature of the relations among the biosecurity actions carried out in different partnerships (for example if they are complementary or substitutes). It is necessary that the scheme works towards reinforcing biosecurity-weak industries or areas and avoids redundant and unnecessary compensation in cases where industry schemes are a better fit.

2.8 Conclusion

We evaluate analytically the role of private–public contracts as a novel instrument in plant pest and disease management, using contract theory. We develop a principal-agent model with the public sector and two private agents, where the government makes payments to the agents in order to encourage private biosecurity actions while lowering the risk of pest outbreaks. Our results show that contracted payments can be designed to spread the economic risk across signatories. The framework allows us to understand how the public sector can harness increased private biosecurity measures by making payments to agents which depend both on their performance and that of the other stakeholders. Moreover, the optimal level of payment depends on the individual agent’s capacity to derive private benefits from healthy plants. When private agents can appropriate a large proportion of the benefits, the government is not required to offer payments to the agents for their surveillance and control efforts. However, the government needs to increase compensation payments if uncertainty increases and when the agents are more risk averse. Lastly, while the goal of the paper is not to provide a detailed description of real world contracts, the article demonstrates the usefulness of contract theory for conceptualising contracting problems in biosecurity with an aim to encourage further discussions on the use of formal contracts to encourage private biosecurity actions.

There is growing interest in contingency plans for plant and animal pests and diseases, specifically on policies that encourage risk reduction (Gilligan et al., 2013; Food Chain Evaluation Consortium, 2010). There is a need to explore new policies capable of encouraging preventive measures, engaging all stakeholders, facilitating early response, and minimising risk. We show that contract theory analysis can provide a basis for the understanding of biosecurity roles and responsibilities by public and private agents, the gaps between these, and the design of schemes that aim to achieve socially desirable outcomes. Our analytical model provides a foundation to stimulate further contributions to apply contracting methodology, and to develop empirical tools for testing contract theory to answer important policy questions regarding biosecurity.

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Chapter 3 - The role of government in supporting voluntary biosecurity schemes

3.1 Preface

In Chapter 2, I investigated the role of contracted payments in delivering a responsibility and risk sharing approach to incentivise individual private efforts towards biosecurity, using a principal-agent framework. The model allowed me to analyse how to structure compensatory payments for higher biosecurity and risk-sharing benefits. My next research objective was to model cost-sharing within a PPP framework. Initially, I explored using the same framework from Chapter 2, by relaxing and expanding how agents are characterised and how their actions would contribute to plant health. However, after deliberation and failed attempts, it was apparent that principal-agent models are very restrictive and quickly become analytically untraceable. Additional research of alternative mathematical tools concluded that a game theory would be able to circumvent those challenges and allow me to focus on how private agents could be incentivised top participate in biosecurity cost-sharing schemes. Thus, this Chapter uncovers the role of the public sector in incentivising private actions towards biosecurity, thus illustrating who PPP schemes could deliver cost-effective management approaches to plant health.

The increasing threat of damaging pests and diseases, and the consequent imposition of stringent and costly regulatory control measures, has inspired alternative industry-led approaches to biosecurity, such as the use of voluntary industry schemes aimed at reducing the probability of outbreaks. Such schemes can be attractive because they encourage a pro-active cooperative approach; however, they can also be perceived as ineffective because they struggle to encourage private actions towards biosecurity. In this Chapter I set out to explore the effectiveness of such initiatives in achieving a reduction in the probability of an outbreak, and focus on exploring the role of government in encouraging scheme participation through a cost-sharing approach.

To achieve this aim, I developed a framework borrowing from the non-cooperative coalition formation theory. I show that, without government payments or the existence of ancillary biosecurity benefits, free-riding overpowers private incentives to contribute to biosecurity. However, while compensation payments incite the formation of larger biosecurity groups, they can discourage individual efforts. Similar to the findings in Chapter 2, I found that pre-agreed terms of payments aimed at partially compensating the costs of private efforts rather than damages, together with a joint strategy of government efforts to prevent the occurrence of an outbreak delivers a cost-effective policy. Overall, the work shows the benefits of cost and responsibility sharing deeds in delivering a cost-effective approach to biosecurity, and provides a theoretical framework to stimulate further exploration of the role of government policies in supporting industry schemes.

This paper was written in the style of Journal of Environmental and Resource Economics, to which it was submitted for publication and it is under review.

I declare that the work submitted is my own. The contribution of the co-author is as follows:

Dr. Julia Touza and Dr. Jon Pitchford: Supervision, review and editing

THE ROLE OF GOVERNMENT IN SUPPORTING VOLUNTARY BIOSECURITY SCHEMES

3.2 Abstract

Voluntary private-public biosecurity schemes are attractive policies because they encourage pro-active cooperation. However, they are often perceived as ineffective because they lack incentives for private engagement. In this paper, we explore the role of the public sector in encouraging private biosecurity efforts through the subsidisation of voluntary biosecurity schemes. The goal is to understand how self-enforcing stable coalitions form under different government strategies: public investments towards reducing the probability of outbreak (e.g. pre-border security checks), or by compensating members' private damages in the case of an outbreak. We show that without government support or the existence of private ancillary biosecurity benefits, free-riding overpowers private incentives to contribute to biosecurity. Furthermore, results demonstrate that compensation payments can effectively incentivise the formation of large stable biosecurity coalitions, but they can also discourage biosecurity efforts by members. A strategy which combines small compensation payments to scheme members with general government-funded biosecurity efforts is the most cost-effective policy to reduce the probability of outbreaks and minimise their economic consequences.

3.3 Introduction

It is widely accepted that both the public and private sectors have a role to play in biosecurity (Mumford, 2011; Anderson, 2005; Cook et al., 2010; Lansink, 2011). However, there is a debate about the balance between the two. For example, a governmental animal or plant health agency within a pure market-oriented economy might distort the market or, if prevention and control efforts are left to the private sector, this will likely result in their under-provision due to the public nature of disease and pest controls (Epanchin-Niell and Wilen 2014; Perrings et al., 2002; Hennessy, 2008; Touza and Perrings, 2011). One of the most common government approaches towards pest and disease outbreaks is the use of post-incursion government compensation payments (Bielza Diaz-Caneja et al., 2009; Garrido and Bielza, 2008). However, *ad hoc* payments have been criticised because they can perversely reduce the cost to farmers and discourage disease avoidance (Perrings et al., 2014; Barnes et al., 2015; Fraser, 2018). Instead, focusing on prevention methods and encouraging early and rapid action in response to any potential outbreak is generally recognised as being more effective (McNeely et al., 2001; Leung et al., 2002; Heikkilä and Peltola, 2004; Sims and Finnoff, 2013).

Prompted by this challenge, voluntary private and public partnerships (PPPs), where costs and responsibilities of prevention and control are shared, are an increasingly appealing policy option (Meuwissen et al., 2013). In such arrangements, the government's role is to act as a supporting body by encouraging private agents to invest in biosecurity, thereby enhancing surveillance, improving communication and building trust, and gaining more information on the status of the outbreak (Cook et al., 2010). PPPs have been described as one of the most cost-effective and adaptive methods to deal with incursions and outbreaks (Cook et al., 2010; Mumford, 2011). In addition, they often promote collaborative stakeholder participation by expanding the decision making to the wider community, thus bringing real-life perspective and valuable knowledge (Koontz, 2005; Patel et al., 2007; Reed and Curzon, 2015). Examples include the Australian EPPRD system (Plant Health Australia, 2014), or the Western Australian Recognised Biosecurity Groups. The European Union (EU) is promoting the use of subsidised PPPs within the Common Agricultural Policy (Liesivaara and Myyrä, 2014).

While voluntary PPPs are attractive because they split costs and encourage a pro-active cooperation approach that could reduce potential conflicts between the regulator and private stakeholders (Segerson and Miceli, 1998), they may be perceived as ineffective because they lack both incentives for participation, and sanctions for non-compliance (Lyon and Maxwell, 2001). Such schemes may struggle to recruit sufficient members to generate worthwhile benefits for the industry because incentives to free-ride can be strong. For example, the number of currently active private-public cost sharing schemes is low (OECD, 2013) and the schemes tend to have either a high (>80%) or a low (<10%) rate of participation, with cases of broad membership being achieved through mandatory policies (Civic Consulting, 2006; Heikkilä and Niemi, 2009). Therefore, it is important to understand how a government can incentivise private individuals not to defect on biosecurity efforts, thereby increasing global benefits (Ostrom, 1990; Janssen and Ostrom, 2006; Graham et al., 2019).

In this paper we study the government's role in encouraging private biosecurity investments through private-public biosecurity schemes. The goal is to understand whether and how guaranteeing post-outbreak compensation payments to agents who join biosecurity schemes enhances the formation of self-enforcing stable biosecurity coalitions. The trade-offs between governmental expenditure on measures that reduce the general probability of an outbreak (e.g. pre-border security checks and inspections), and compensation payments to members for damages in the event of an outbreak, is also explored. Our work informs policy decision making when prioritising budgets for plant and animal health and contributes more generally to the work on modelling contractual PPPs for biosecurity. The novelty of the paper lies in its implementation of a coalition formation game from non-cooperative theory in order to quantify potential synergies of public and private biosecurity investments. Whereas there is a rich literature analysing coalition formation in game theory (Barrett, 1994; Finus, 2001), previous work focused on when defection or cooperation is sustained in a biosecurity setting often employed optimal control and evolutionary games (Fenichel et al., 2014; Nowak, 2006; Touza et al., 2013; Enright and Kao, 2015; Epanchin-Niell and Wilen, 2014; Büyüktahtakin et al., 2013). We instead follow the recent interest in how coalition formation can be encouraged through the role of financial supporter (Ansink et al., 2017).

We find that without government support or the existence of private ancillary biosecurity benefits, free-riding overpowers private incentives to contribute to prevention efforts. Moreover, we find that the use of such compensation payments can improve overall biosecurity by encouraging larger coalitions, provided that they are set a-priori in a PPP agreement, and only partially cover the private costs of biosecurity of scheme members. The most cost-effective policy requires a combination of compensation and government prevention efforts. Importantly, we also show that full participation by all private agents in the scheme is not necessary to achieve a cost-effective reduction in the probability of an outbreak.

3.4 Methods

We first explore whether farmers would voluntarily join a scheme that requires members to make biosecurity investments in order to reduce the probability of an outbreak. Following this, we investigate how different government strategies affect the decision of the agents and, consequently, the total biosecurity level and probability of an outbreak. We assume that a successful biosecurity scheme is characterised by a large number of members, an increase in the overall level of biosecurity, and a decrease in the probability of an outbreak, all while minimising government expenditure. The trade-offs involved between the government and private incentives and consequent biosecurity investments are explored using the framework of coalition games (e.g. Carraro and Siniscalco, 1993; 1998, Barrett, 1994). Ansink et al. (2017) expanded the standard coalition game of non-cooperative theory to allow coalition formation with financial incentives by modelling “supporting” agents. They show that financial support can increase the payoffs of all agents: members, supporters and free-riders. In this paper, we restrict the number of supporters to one, the government, but its role and the form of support is modelled explicitly.

3.4.1 Model elements and stages

Consider a set $N = \{1,2,3, \dots, n\}$ of identical independent agents. Agents are offered the opportunity to join a biosecurity scheme. Each coalition member is required to make a biosecurity investment, ϕ, which reduces the probability of an outbreak[12]. Similarly, each coalition member is entitled to a compensation payment, τ, in the event of an outbreak. Agents which decide not to join the scheme are considered as free-riders. The probability of the outbreak varies between exogenously fixed maximum and minimum probabilities, and decreases along this range as the total biosecurity investment increases. The total biosecurity effort (I) is given by the sum of individual private investment efforts, ϕ, and government biosecurity investments, G, so that for a coalition with m members, the total investment is: $I = m\,\phi + G$. We denote the probability of an outbreak as $p(I)$ and the probability of not having an outbreak is $\left(1 - p(I)\right)$. We thus assume that each member's biosecurity efforts create a positive externality by reducing the likelihood of outbreak faced by all individuals.

The problem is modelled as a three-stage game:

Stage 1: The government decides its biosecurity strategy: it chooses its biosecurity investment, G, which lowers the probability of the outbreak for all, regardless of coalition membership; and how much to pay agents who have joined the scheme in the event of an outbreak, τ.

Stage 2: Given the government strategy $\{G, \tau\}$, each agent independently decides whether or not to join the scheme based on expected payoffs. We denote the decision by $\mu_i \in \{0,1\}\ \forall i \in N$ with the interpretation that if $\mu_i = 1$, agent *i* would join and otherwise not. The outcome of this stage is a set $M = \{i\colon \mu_i = 1\}$ which comprises of all members in the scheme. The number of joiners is denoted $m = |M|$. The non-joining agents are free-riders $F = N\backslash M$. The free-riders benefit from reduced probability of outbreak thanks to biosecurity investments made by joiners and the government.

Stage 3: Members choose their level of biosecurity investment, ϕ. Individual investments add up to a total biosecurity investment level: $I = m\,\phi + G$. The state of the world is realised, and payoffs are determined. Note that agents decide whether or not to join the scheme and their optimal biosecurity investments before the outbreak occurs[13].

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[12] For example, efforts towards early detection and rapid action are usually considered a major contribution factor to reducing the likelihood of outbreaks and mitigating impacts (Kaiser and Burnett 2010).

[13] There is increasing interest in contingency (a-priori) management arrangements between the government and the private sectors intended to reduce the response time thus minimising the size and impact of the incursion (DEFRA, 2018).

3.4.2 Payoffs

We assume that members derive private ancillary benefits from their own biosecurity efforts $b_p(\phi)$, and face costs from their biosecurity efforts, $c_p(\phi)$. $c_g(G)$ represent the cost of the biosecurity efforts employed by the government. In the event of an outbreak, both free-riders and members suffer constant damages, δ_p, and the government suffers damages of δ_g, for example related to ecosystem services losses or proactive management to mitigate impacts. Each agent joining the biosecurity scheme is entitled to a compensation payment τ from the government in the event on an outbreak.

The expected payoff of a given free-rider is given by:

$$E_F \; = \; p(I)\big(-\delta_p \big) \quad \forall\, i \, \in F \quad \text{where}\, F = N \backslash M \qquad (1)$$

The expected payoff of a representative member is:

$$E_M \; = \; p(I)\big(\, b_p(\phi) - c_p(\phi) - \delta_p + \tau \big) + \big(1 - p(I)\big) \Big(\, b_p(\phi) - c_p(\phi) \Big) \quad \forall\, i \, \in M \qquad (2)$$

The government's payoff is given by the expected compensation payments that it transfers to members of the biosecurity scheme and the social damages in the event of an outbreak, and the costs of investing in national biosecurity, *G*. The expected payoff of the government is:

$$E_{gov} = \; -Tp(I) - c_g(G) - \delta_g p(I) \qquad (3)$$

where *T* is the government's total compensation expenditure in the event of an outbreak: $T = m\,\tau$.

3.4.3 Solving the game

We solve the game by backwards induction, starting by understanding how coalition members should choose the optimal biosecurity levels given knowledge of the other variables. Thus, in stage 3, optimum levels of biosecurity are determined from the best response functions of members. Each agent takes investment levels by all members as given and chooses its individual biosecurity. The best response function of members and optimal biosecurity investment levels is given by the first order derivative condition:

$$\frac{\partial E_M}{\partial \phi} = b_p'(\phi) - c_p'(\phi) + mp'(I)(\tau - \delta_p) = 0 \qquad (4)$$

Under the assumption that the investment game has a unique equilibrium, each member's equilibrium investment can be written as a function of the number of members:

$$b_p'(\phi) + \tau m\, p'(I) = c_p'(\phi) + \delta m p'(I) \rightarrow \phi^* \qquad (5)$$

This can be solved to give an optimal level of biosecurity for each member, ϕ^*. Optimal biosecurity investments are achieved when marginal benefits (ancillary benefits and transfers in the event of an outbreak) are equal to marginal costs (costs of investments and costs from damages). We also require that the level of biosecurity investments needs to be positive, $\phi^* \geq 0$. Otherwise, agents would be tempted to join the scheme but to invest negatively, corresponding to corrupt behaviour designed to benefit from compensation payments. Total optimal global investment levels are $I^* = m\phi^* + G$.[14]

Let $E_M(m)$ denote the expected payoffs of agent *i* obtained from biosecurity investments when agent *i* and *m-1* other agents are in the scheme. Similarly, let $E_F(m)$ denote agent *i*'s payoffs obtained from investments if agent *i* is not in the scheme formed by *m* other agents.

A member's payoff and a free-rider's payoff are defined as:

$$E_M^*(m) = p(I^*)\big(b_p(\phi^*) - c_p(\phi^*) - \delta_p + \tau\big) + \big(1 - p(I^*)\big)\Big(b_p(\phi^*) - c_p(\phi^*)\Big) \quad \forall i \in M \qquad (6)$$

---

[14] It is important to note that, as the government does not optimally decide its strategies $\{G, \tau\}$, optimal total investments in biosecurity are a sum of private agent investments, $m\phi^*$, and government biosecurity efforts, G.

$$E_F^*(m) = \ p(I^*)\big(-\delta_p\big) \quad \forall\, i\ \in F \qquad (7)$$

In stage 2 we determine the equilibrium number of members and free-riders given expected payoffs and optimal investments. A Nash equilibrium in membership strategies implies that no member would like to deviate from $\mu = 1$, and no free-rider would like to deviate from $\mu = 0$. Put simply, under these conditions nobody wants to join the scheme, and nobody wants to leave. The conditions for internal (8) and external stability (9) are:

1) No free-riders would wish to join: $E_F^*(m) \geq E_M^*(m+1)$ (8)

2) No member would seek to leave: $E_M^*(m) \geq E_F^*(m-1)$ (9)

The last step is to determine the government strategies $\{G, \tau\}$ necessary to support a stable coalition. We can thus identify all m such that (8) holds for τ and G. Of the internally stable coalitions, we can identify the subset which is also externally stable such that (9) is satisfied. Because optimal private investments depend on compensations and government investments, we cannot analytically solve for the government strategies, but they need to satisfy the following conditions:

$$\tau \geq \frac{m\,(E_F^*(m-1) - E_M^*(m))}{p(I^*(m))} \qquad (10)$$

$$\tau \leq \frac{(m+1)(E_F^*(m) - E_M^*(m+1))}{p(I^*(m+1))} \qquad (11)$$

Solutions to the above equations give the compensation levels and government investments that support stable biosecurity schemes where members also invest in biosecurity $\{G^*(m), \tau^*(m)\}$. Compensation has to be high enough for members not benefitting from leaving and free-riding (eq.10), but small enough that no free-riders want to join (eq. 11).We denote the set of internally and externally stable coalitions under compensation τ and government support by $\mathcal{M}(T, G)$. To test that $\mathcal{M}(T, G)$ is non empty, for a given $\{G^*(m), \tau^*(m)\}$, if external stability is violated for m, then internal stability holds for $m+1$, and we can apply this argument until (8) holds or the set of potential members is exhausted $m = n$.

3.5 Applications with common model specifications

In this section we apply the model to illustrate how the government's strategy can affect the formation of a biosecurity coalition. We specify linear benefits and quadratic biosecurity costs, as commonly used in the literature (e.g. Barrett, 1994; Rubio and Ulph, 2006; Ansink et al., 2017). We assume that, in addition to the primary benefits of biosecurity in terms of lowering the probability of the outbreak, biosecurity efforts may generate ancillary or secondary benefits (Pittel and Rubbelke, 2008). Primary benefits are the benefits derived from pursuing biosecurity policy's primary aim of reducing the probability of the outbreak. In contrast, ancillary benefits are exclusively enjoyed by individual agents who invest in biosecurity, such as direct monetary production benefits or non-monetary benefits from further awareness of risks along an agent's own supply chain. The costs of biosecurity are only borne by those who exert efforts (i.e. members and the government). Thus, $b_p(\phi) = \beta_p\phi$ and $c_p(\phi) = \frac{1}{2}\gamma_p\phi^2$, where β_p are marginal ancillary benefits, and γ_p are marginal costs of biosecurity. As stated in Section 3.3, damages in the event of an outbreak are constant, δ_p, and per member compensation payment is τ in the event of an outbreak.

We assume that there is a maximum probability of outbreak, and that this decreases exponentially with investments in biosecurity, up to a minimum outbreak probability, following Bate et al. (2016). Thus $p(I) = p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}$, where k is the rate at which investments in biosecurity reduce the probability of outbreak. Total biosecurity is given by the sum of investments from agents and government: $I = m\phi + G$.

Expected payoffs of free-riders, members and the government become:

$$E_F = -\delta_p(p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}) \quad \forall\, i \in F \quad where\; F = N\backslash M \tag{12}$$

$$E_M = \beta_p\phi - \frac{1}{2}\gamma_p\phi^2 - \delta_p(p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}) + \tau\,(p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}) \quad \forall\, i \in M \tag{13}$$

$$E_S = -m\tau(p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}) - \frac{1}{2}\gamma_g G^2 - \delta_g(p_{min} + (p_{max} - p_{min})e^{-k(m\phi+G)}) \tag{14}$$

The best response function of members and optimal biosecurity investment levels is given by:

$$\frac{\partial E_M}{\partial \phi} = \beta_p - \gamma\phi + \delta_p km(p_{max} - p_{min})e^{-k(m\phi+G)} - \tau km(p_{max} - p_{min})e^{-k(m\phi+G)} = 0 \qquad (15)$$

It is not possible to solve the model analytically. Numerical solutions are produced using MATLAB; the nonlinear solver 'fsolve' is used to find the solutions to finding the optimal levels of biosecurity investments that solve $\frac{\partial E_M}{\partial \phi} = 0$. We repeat this exercise for all coalition sizes, for a range of compensation payments and for a range of government biosecurity investments.

After obtaining optimal biosecurity investments, we calculate expected payoffs for members, free-riders and members, by substituting the optimal member biosecurity investments into eq. 12-14. For all the compensation payment levels and government investments, we evaluate which coalitions are stable. The stability conditions for $M \in [2, N-1]$ members occur when no free-riders would wish to join and no member would seek to leave (eq. 8-9). Note that for $M = 1$, only the first condition is needed for stability, whereas for $M = N$, only the second condition is needed for stability.

3.6 Results

The results in Figures 3.1-3.7 provide a summary of the stable self-enforcing coalition sizes and the consequent reduction in outbreak probability, both of which are measures of success of the scheme, under a range of policy scenarios. Firstly, we focus on how coalitions form under no government support and no ancillary benefits (*Scenario a*). Secondly, we explore the role of the government in supporting the creation of biosecurity coalitions, the reduction in the probability of outbreak, and the cost-effectiveness of alternative policies (*Scenario b*). We then assess how these results are affected when agents can appropriate ancillary benefits from biosecurity investments (*Scenario c*).

The model parameter values, which ought to be understood as broadly indicative rather than relating to a particular situation, are given in Table 3.1. They illustrate sets of values that capture changes in the optimal joining decision of agents, and the sensitivity of these decisions to the underlying parameters. Thus, we avoid parameter combinations that result in uninteresting results, such as cases when the benefits of investing in biosecurity incite all agents to always join the coalition, or the opposite extreme where biosecurity investment is never favourable. Note that in practice, compensation amounts are often equivalent to the disease-free value of the stock (Fraser, 2018)[15]. For our simulations, we included a set of compensation values ranging from 0 up to δ_p, where agents would receive full compensation for the damages suffered. The parameter value used for the probability of outbreak is similar to that considered by Fraser (2018) and Bate et al. (2016). We include an analysis of the robustness of our qualitative results to changes in parameter values.

Table 3.1 Parameter values used in numerical simulations

Parameter values for simulation

Scenarios		**A**	**B**	**C**
Marginal private benefits of biosecurity investments	β_p	0	0	[0,1,2,5,10]
Marginal costs of biosecurity investments for members	γ_p	2	2	2
Marginal costs of biosecurity investments for government	γ_g	0	0	2
Minimum probability of outbreak	p_{min}	0.1	0.1	0.1
Maximum probability of outbreak	p_{max}	0.5	0.5	0.5
Rate at which biosecurity investments reduce probability	k	0.1	0.01	0.01
Private fixed damages in event of outbreak	δ_p	10	10	10
Social fixed damages in the event of an outbreak	δ_g	0	10	10
Total agents	N	50	100	100

3.6.1 Scenario A: Biosecurity coalitions under no government support

This scenario provides a baseline for later exploring the effect of different type of government interventions to support industry-led scheme initiatives. We thus focus on how coalitions form without any government support and when biosecurity efforts only create benefits in terms of a reduction in the probability of outbreak[16]. Biosecurity efforts are thus a pure public good: the benefits of a reduced outbreak probability are enjoyed by all agents, while only those who conduct efforts, i.e. members, incur the costs.

Under this scenario, the expected payoff of members and free-riders only differs in that members face costs for their optimally chosen investments, making $E_F \geq E_M$ to hold for any coalition size (Figure 3.1). Despite this, there is a small stable coalition of size m^* = 3 (i.e. a membership rate of 6%), achieving a reduction in the probability of the outbreak of approximately 10%.

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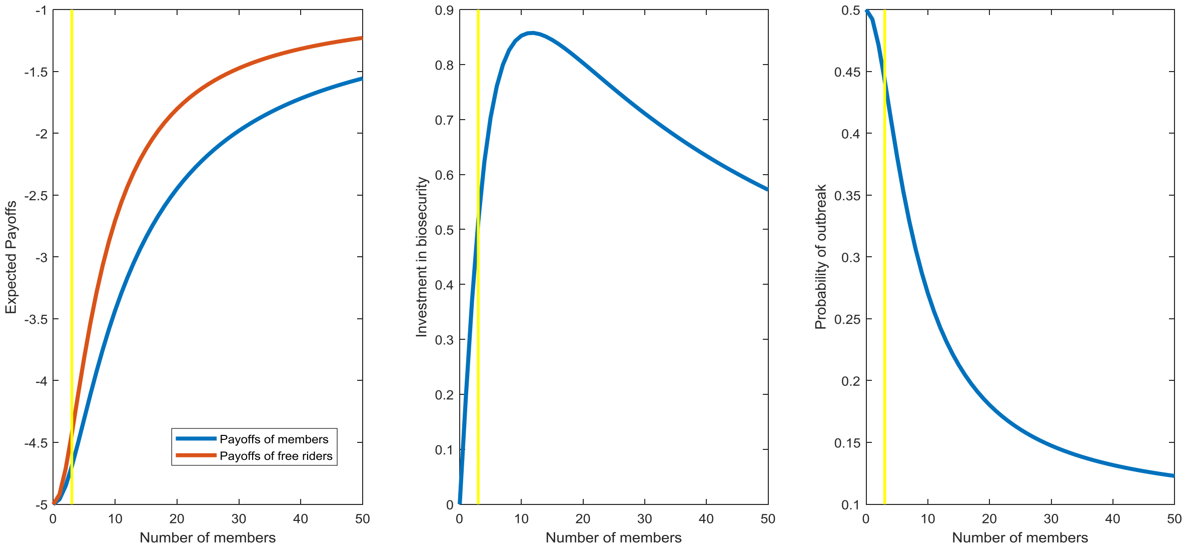
[15] Other compensation structures match the full cost of farmer's control and eradication efforts, such as Recognised Biosecurity Groups in Western Australia.

[16] Because the aim of this scenario is to provide a baseline of what an industry scheme would achieve without the support or private ancillary benefits, we overlook the impacts on the government.

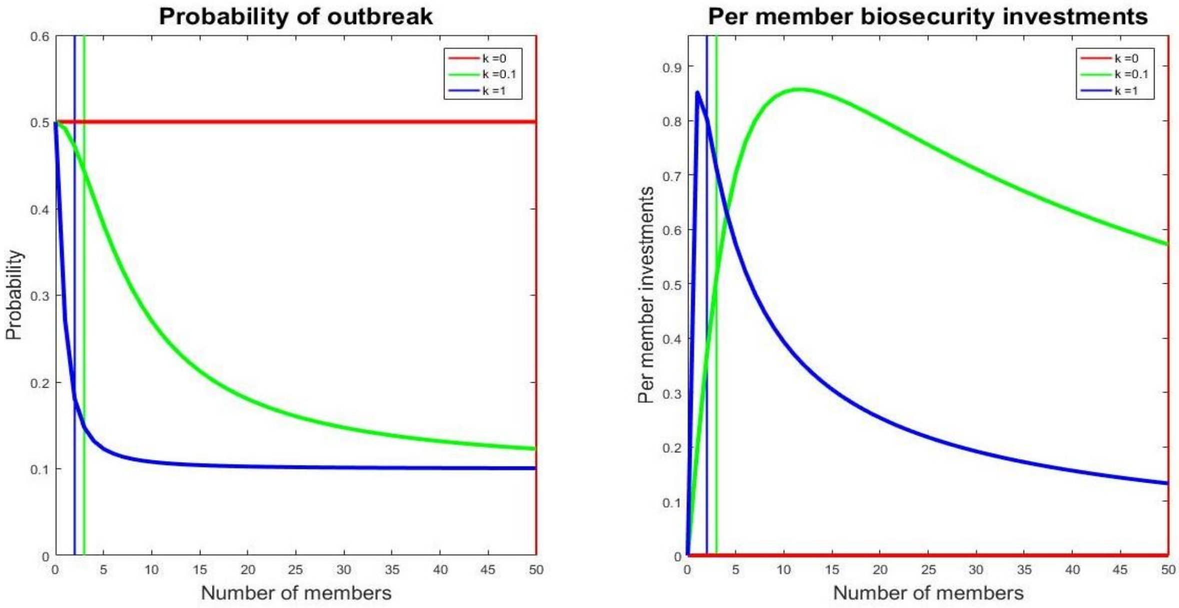
Figure 3.1a shows the expected payoff of members and free-riders change for different coalition sizes. As the coalitions get bigger, the expected payoff for both members and free-riders increases, i.e. everyone one is better off when biosecurity schemes have large memberships. For all coalition sizes, the expected payoff of free-riders is always equals or exceeds that of members. The difference between the expected payoff of members and free-riders increases as coalition size increases, up to a point. As coalition size becomes large, the difference in expected payoffs becomes smaller. This effect occurs because while coalitions are small, per member investments are relatively larger, compared to per member investments in very large coalitions. Figure 3.1b shows the optimal per member investment in biosecurity at different scheme membership sizes. For small coalitions (20% membership or less), per member investment increases, but as the coalition size gets larger, the per member investment decreases. Figure 3.1c shows the probability of outbreak over different coalition sizes. The probability of outbreak decreases rapidly for each incremental coalition size, and approaches the minimum probability as the coalition size increases.

Figure 3.1 Only a small biosecurity coalition forms under no government support or ancillary benefits, with minimal impact on reducing the probability of outbreak. The yellow vertical line marks the largest stable coalition size. Figure 3.1a plots expected payoffs of members and free-riders for a range of coalition sizes. Figure 3.1b plots per member optimal investment in biosecurity efforts for a range of coalition sizes. Figure 3.1c plots the probability of outbreak for a range of stable coalition sizes.



An important model parameter that directly affects damage risk and thus expected payoffs is *k*, the rate at which biosecurity investments affect the probability of outbreak. *k* could be described as the effectiveness of biosecurity efforts to reduce potential outbreaks. Higher values means that efforts are very successful in reducing the probability and lower values represent cases when biosecurity efforts have small effect on biosecurity (perhaps because non yet present a disease has multiple hosts affecting several industries and thus efforts have a low impact in the probability of an outbreak given the challenges of prevention under this scenario). Figure 3.2 shows how different values of k affect the probability of outbreak. As k increases, the stable coalition size decreases. This is because each unit of biosecurity effort is more successful in reducing the outbreak probability, strengthening the free-riding effect as k increases (largest stable coalition is 4% membership; $m^* = 2$). As k increases, per member biosecurity investments peak at lower coalition sizes and decrease at a faster rate as the coalition size increases (Figure 3.2b). A special case occurs when $k=0$; in this case there are no benefits from biosecurity and so it is optimal for members to not invest, $\phi^*=0$. This makes the expected payoff of free-riders and members the same, $E_F = E_M$. Trivially, all agents join the coalition ($m^* = 50$), but no biosecurity benefit is achieved.

Figure 3.2 Effects of the rate, *k*, at which biosecurity reduces the probability of outbreak on the probability of outbreak (Figure 3.2a) and on optimal per member biosecurity investments (Figure 3.2b). The vertical lines mark the largest stable coalition size for the different values of *k*.



The effects of other parameter changes on coalition formation are as one might intuitively anticipate, and may be summarised as follows: as damages δ_p increase, coalition size decreases; as marginal costs of biosecurity efforts γ_p decrease, stable coalition size decreases briefly, and then increases; and as the gap between p_{min} and p_{max} increases, coalition size decreases.

To conclude, this scenario illustrates the problems faced by industry-led schemes in gathering members, particularly if the biosecurity contributions are pure public goods. The free-riding effect overpowers the potential positive benefits from joining a scheme. In short, agents must be able to derive additional rewards to incentivise voluntary efforts in biosecurity. The following subsection explores how the government could make voluntary biosecurity schemes more appealing to agents by providing compensation payments to members, and explores how the amount of compensation affects membership and biosecurity achieved by the coalition.

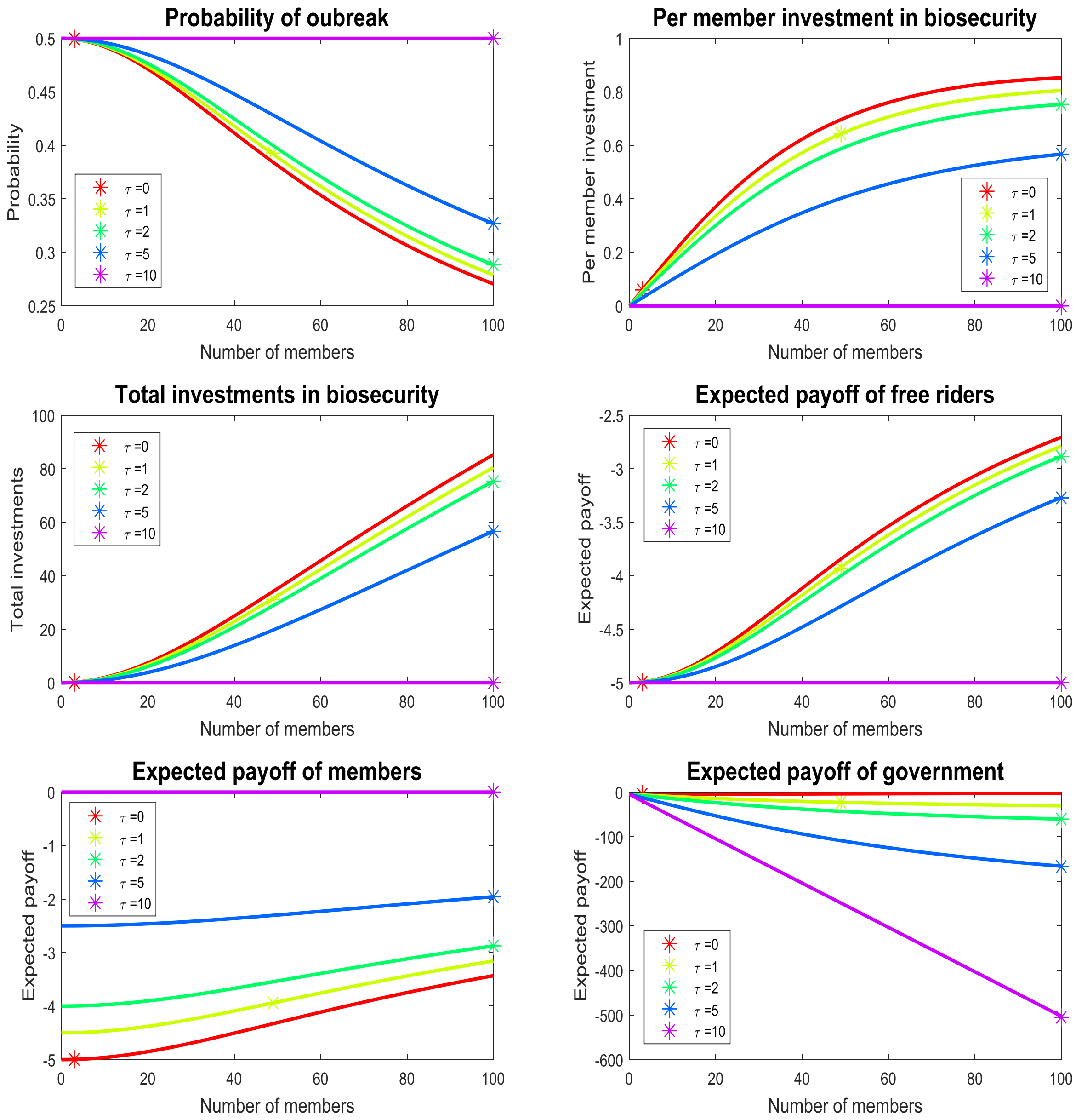
3.6.2 Scenario B: Biosecurity groups with government support

Figure 3.3 shows how different levels of government compensation payments to coalition members influence expected payoffs, the probability of outbreak, biosecurity investments, and coalition size. Higher payments support larger stable coalitions, as expected. Results show that even with compensation amounts substantially smaller than damages (for example, matching the marginal cost per unit of member's biosecurity investment costs) the scheme is transformed from attracting just 3 members under *Scenario a* to full membership under *Scenario b* (Figure 3.3a).

However, while compensation payments increase the size of the coalition, this increase in membership does not necessarily translate into a reduction in the probability of outbreak. This is because, as the amount of compensation increases, the per member optimal level of biosecurity investment decreases. Though a reduction in the probability of the outbreak is achieved because larger stable coalitions are formed, payments have an adverse effect on agents' biosecurity incentives: members invest only minimally in biosecurity in order to not lower the probability of outbreak and thus be eligible for compensation in the event of an outbreak. Therefore, there is a trade-off between the negative effect that compensation payments have on optimal member biosecurity investments and the support of voluntary private biosecurity schemes. At the level where compensation payment matches damages, the probability of outbreak stays at p_{max} and coalitions, while successful in gathering members, have no real effect on biosecurity. On the opposite side, with no or very low compensation, coalitions are too small to cause any useful reduction of the outbreak probability.

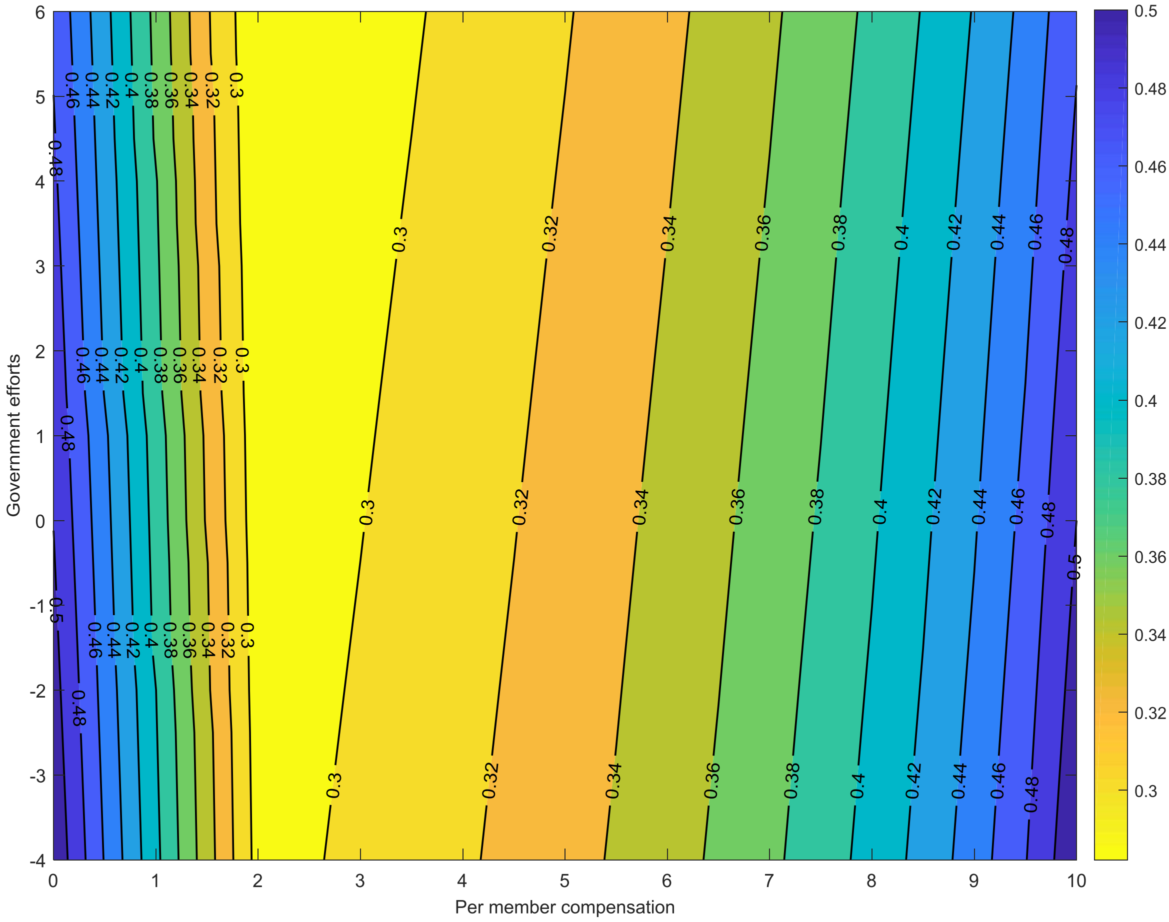
The adverse effect can also be seen in the expected payoff of free-riders, which decreases as government payments increase (Figure 3.3d). Moreover, the expected payoff of the government decreases as compensation payments increase (Figure 3.3f) due to incurring large expenditures in compensation payments while the probability of the outbreak is high. The expected payoff for members increases with higher compensation payments (Figure 3.3e).

Figure 3.3 Effects of five different government compensation payment levels on probability of outbreak (3.3a), per member investment in biosecurity (3.3b), total investment in biosecurity (3.3c), expected payoff of free-riders (3.3d), members (3.3e), and government (3.3f), for different coalition sizes. The asterisk represents the largest stable coalition size under the specified government compensation payments (**τ**).



Governments often have to make decisions on how to best use resources to tackle outbreaks. Thus, if resources are invested supporting industry schemes by compensating members, it could sometimes translate into a reduction in outbreak prevention activities. Understanding the trade-offs and cost-effectiveness among different government strategies is a crucial to ensure governments tailor biosecurity policies appropriately. Figure 3.4 shows the resulting probability of outbreak in a more realistic scenario, where policies combine incentives to private biosecurity practices and direct public expenditure on biosecurity. Negative ranges for government efforts were also included to illustrate budget restrictions, for example when resources are diverted towards compensation and away from investments towards biosecurity. The probability of outbreak decreases with increased per member compensation up to a point, and starts increasing for higher amounts or compensation; it also declines with increasing government investments.

Figure 3.4 Reduction in the probability of outbreak for different levels of government biosecurity efforts (G) and compensation amounts to biosecurity scheme members ($\boldsymbol{\tau_i}$).

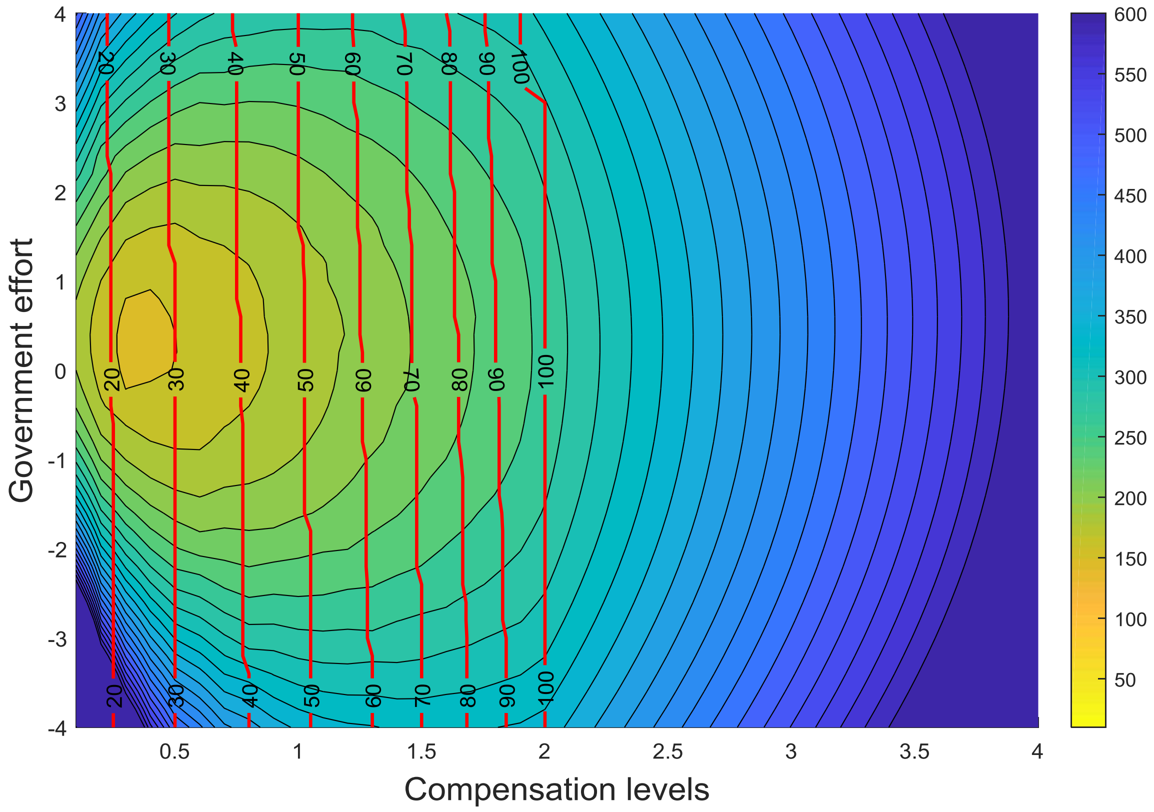


However, in order to compare both policy options, we calculated the cost effectiveness for a combination of government policies. The cost effectiveness of each policy was calculated as the cost to the government per additional reduction in the probability of outbreak:

$$\text{Cost effectiveness} = \frac{E^*_{gov}(\tau, G, m^*)}{p^*(\tau, G, m^*) - p^*(\tau = 0, G = 0, m^*)} \qquad (16)$$

Figure 3.5 demonstrates that the most cost-effective policy is a combination of small payments and government biosecurity efforts. It is important to note that the most cost-effective policy occurs when the scheme does not have full membership, but instead only 20 to 30% of agents sign up.

Figure 3.5 Cost effectiveness under a range of government policy options. The contour lines denote the cost effectiveness of the policies, as defined by equation (16), and the red lines represent the largest stable coalition size achieved by the combination of policies.

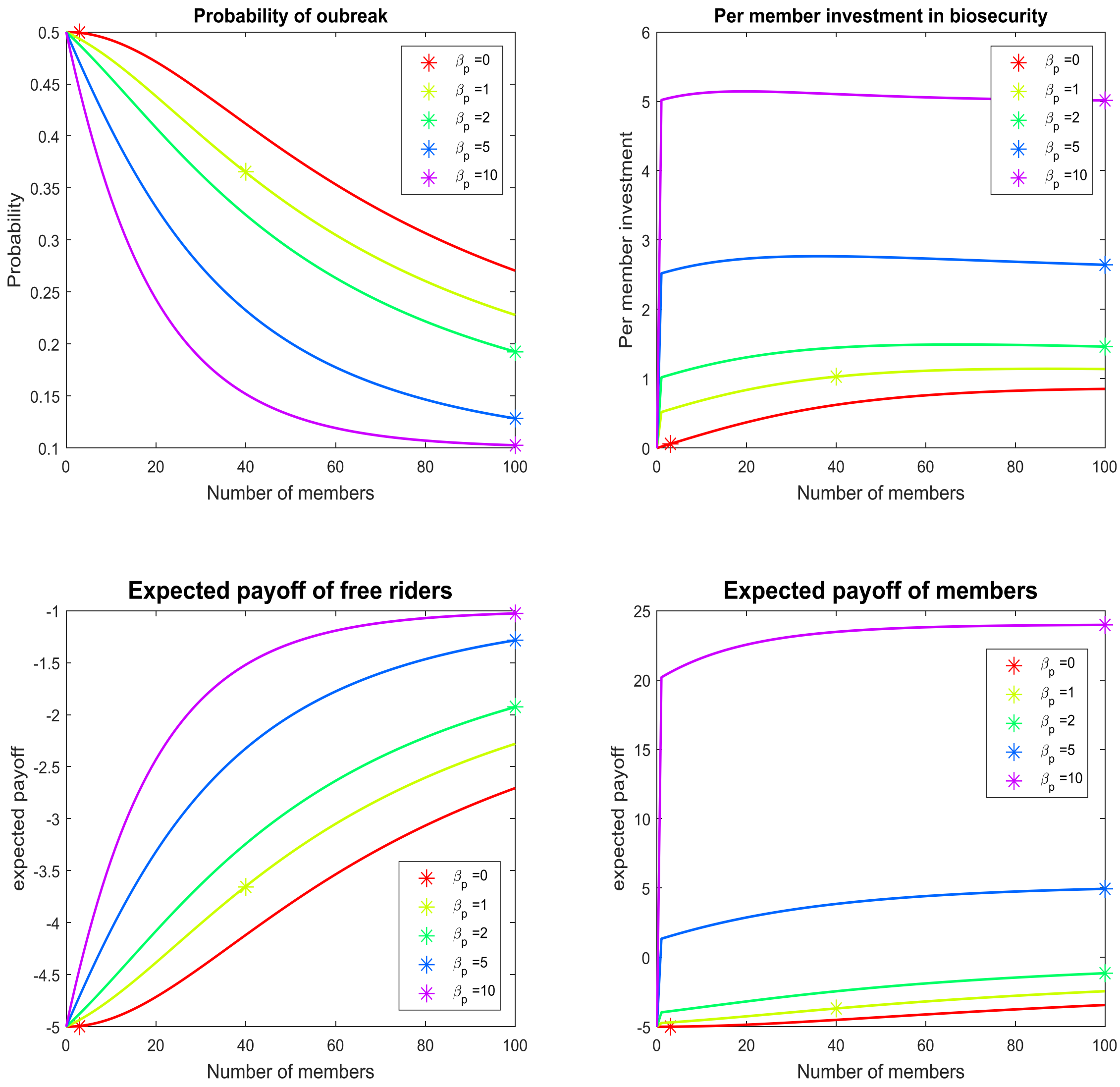


The results in this section demonstrate the benefits of a cost- and responsibility-sharing approach towards biosecurity: concentrating government biosecurity efforts towards single policies is not cost-effective. Moreover, it also illustrates that a scheme does not require full agent membership in order to achieve a potentially important increase in biosecurity. In fact, if the coalition needs government support to encourage agents to join due to the public nature of biosecurity benefits, limited membership would be preferred by the government from a perspective of cost-efficiency.

3.6.3 Scenario C: Biosecurity groups with member ancillary benefits

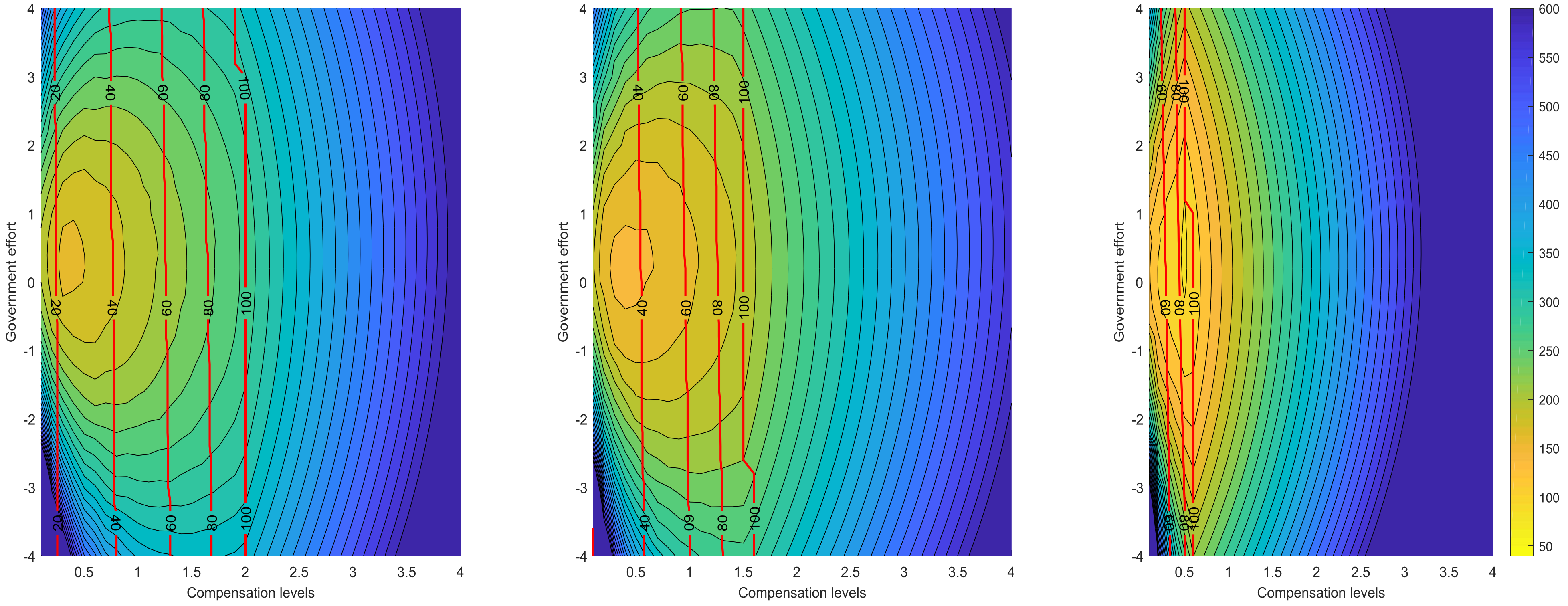
This subsection explores the role of ancillary biosecurity benefits, exclusively enjoyed by individuals who invest in biosecurity, in driving agents to join the scheme and invest in biosecurity efforts. Figure 3.6 illustrates how the capacity of members to appropriate ancillary biosecurity benefits drives agents to join the scheme and invest in biosecurity efforts. This is assessed under a case of no government action (i.e., $\tau = 0, G = 0$), in order to assess whether they are sufficient to support a purely private scheme. We find that as ancillary benefits increase, per member investment in biosecurity increases (Figure 3.6b), as well as the stable coalition size. This leads to a decrease in the probability of the outbreak as co-benefits increase (Figure 3.6a), with high levels of private co-benefits resulting in the outbreak probability approaching p_{min}. The increased biosecurity results in higher expected payoffs to both members and free-riders (Figure 3.6c-3.6d).

Figure 3.6 Effects of member ancillary biosecurity benefits on the probability of outbreak (6a), member investments in biosecurity (3.6b); and expected payoffs of free-riders (3.6c) and members (3.6d), for a range of coalition sizes. The asterisk marks the largest coalition size.



Lastly, we examine the role of government when biosecurity efforts have both public benefits (reduction in the probability of outbreak) and private benefits (additional co-benefits to those who invest in biosecurity). Figure 3.7 shows the cost-effectiveness of government expenditures towards reducing the probability of the outbreak for three levels of private ancillary benefits ($\beta_p = 0, 0.5, 1$). As private ancillary benefits increase, both government policies become less cost-effective. Therefore, if members can appropriate co-benefits from their biosecurity efforts, the government should refrain from offering compensation payments and also reduce its efforts towards biosecurity.

Figure 3.7 Contour plot of the cost-effectiveness of government compensation payments in reducing the probability of the outbreak under different levels of private co-benefits (Figure 3.7a. $\boldsymbol{\beta_p = 0}$; Figure 3.7b. $\boldsymbol{\beta_p = 0.5}$; Figure 3.7c. $\boldsymbol{\beta_p = 1}$). The red lines represent the largest stable coalition size for each combination of government policies.



3.7 Discussion and conclusions

The increasing threat of damaging pests and diseases has inspired alternative industry-led approaches to biosecurity, such as the use voluntary schemes aimed at reducing the probability of outbreaks (Horticultural Trades Association, 2017; Azbel-Jackson et al., 2018; Hop et al., 2011; Waage et al., 2007). However, such industry-led schemes often have difficulties in gathering sufficient members and therefore enough biosecurity benefits for the industry, because incentives to free-ride can be strong (Wolf, 2005). Cost and responsibility sharing schemes, where the efforts are split between the private and public sector, can overcome the previously stated challenges (Waage et al., 2007; Lansink, 2011). However, it is crucial to have a clear understanding of the roles of each party to avoid delayed action and under-provision or crowding-out of efforts (Bremmer and Slobbe, 2011; OECD, 2013). In this paper, we explored the potential role of government in supporting PPPs to attract membership and achieve a reduction in the probability of outbreaks. Our numerical examples illustrate the scope for different types of incentives to improve scheme membership, and also include a cost-effectiveness evaluation to determine the extent to which the government could successfully incentivise biosecurity actions.

We found that without government support, such as members' compensation for outbreak damages, or a member's capacity to derive private ancillary benefits from his efforts, voluntary biosecurity schemes have low membership due to free-riding. Our model illustrates that even small appropriation of co-benefits by members can be sufficient to encourage agents to join a biosecurity scheme. Co-benefits can come from preferential trade between members, since their trading partners are members with higher levels of biosecurity, or conversely, members can sometimes gain a premium on their more biosecure produce (Fearne, 2000). Therefore, if biosecurity efforts are impure public goods, industry schemes can still achieve a reduction in the probability of outbreak, and government support is not needed to encourage private biosecurity incentives.

Increased membership in voluntary biosecurity coalitions can also be achieved through government intervention, by supporting the industry scheme through a cost and responsibility sharing approach. We found that if members and agents agree on a deed outlining the compensation amounts prior to an outbreak, the scheme is likely to gain higher membership and improve biosecurity overall. While the use of compensation for damages is currently under scrutiny from regulators compared to alternative policies that encourage an active role in the prevention and control of pests (Leisevaara and Myyrä, 2014), government support payments have a place in encouraging private biosecurity efforts (Bicknell et al., 1999; Olmstead and Rhode, 2015; Gramig et al. 2009).

However, there is a fine balance, as pointed out by Hennessy and Wolf (2018), that compensation must be large enough to ensure reporting but not too large to discourage biosecurity incentives. Our model illustrates how compensation payments can be structured to deliver public benefits, in terms of a reduction in the probability of outbreak for all, while being a cost-effective policy for the government. We find that pre-agreed compensation payments limited to partially covering the preventative biosecurity effort costs of members avoid the common reported adverse incentives of compensation. For example, farmers received over 1.1£ billion in compensation for slaughtered animals during the Foot and Mouth epidemic (NAO, 2002), and the compensation of full damages was often viewed as part of why efforts failed to control the epidemic (Fraser, 2018; Hennessy and Wolf, 2018). Thus, in line with the previous mentioned literature (Jin and McCarl, 2006; Barnes et al., 2015), we found that there is the potential for reducing current compensation payments and enabling a pre-agreed cost and responsibility approach by diverting part of those funds to further conduct additional government biosecurity efforts, such as inspections and pre-border checks.

Additionally, we find that under a cost and responsibility sharing approach, the most cost-effective scheme only requires partial participation from industry. While it is conventionally perceived by industry that schemes require high, or even full, membership levels to be an effective biosecurity policy (Sutcliffe et al., 2018), our finding is consistent with results from incentive literature. For example, in the subsidised agricultural insurance literature, it is often described that partial uptake is needed for risk sharing (Civic Consulting, 2006). However, those agents actively engaging in the biosecurity scheme must be rewarded to avoid free-riding, either through partial pre-agreed compensation for their efforts or by facilitating the appropriation of biosecurity benefits (HTA, 2019; Liu and Sims, 2016; Enright and Kao, 2015; Wilen, 2007).

In cases where biosecurity efforts are pure public goods, we find that a combined approach of government biosecurity efforts and post-outbreak incentives is the most cost- effective government policy to reduce the probability of outbreaks. This result captures a common theme across the literature on pest management. It is generally agreed that enabling a consistent and coordinated management approach across the public and private sector can reduce costs in the long run, achieving economies of scale and developing combined strategies that otherwise would not be possible (Epanchin-Niell and Wilen, 2014; Liu and Sims, 2016; Waage et al., 2007).

It is important to note that in this model we overlook the dynamics over time of both the disease and biosecurity achieved under the scheme and focused on one-time step. Additionally, we have assumed agent homogeneity, with the only difference among agents being whether they become members or free-riders. Moreover, we assume that government- and agent-level biosecurity efforts are perfect substitutes, whereas often government efforts may be complementary to agents' actions. There is scope for future work to relax these assumptions, and to explore what is the impact of heterogeneity or dynamics on the success and effectiveness of such a scheme. For example, this framework could be used to model the UK horticultural sector, where different business could be simulated having different agent types (some that would be able to derive more benefits or costs from biosecurity than others), and test whether they would join the new Plant Health Assurance Scheme being developed or how much support government should provide.

Moreover, as the number of voluntary biosecurity related schemes increase, it should be carefully considered how the government could best support a network of schemes, where crucial information is shared across schemes and biosecurity efforts are aligned towards an agreed biosecurity objective. Despite these limitations, this work shows the benefits of cost and responsibility sharing deeds in delivering a cost-effective approach to biosecurity, and provides a theoretical framework to stimulate further exploration of the role of government policies in supporting industry schemes.

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Chapter 4 - Understanding stakeholder participation in public-private insurance schemes for pest management

4.1 Preface

The findings of Chapter 3 emphasised the importance of a joint public-private approach towards biosecurity. Industry and policymakers design policies, but those are used by individual agents such as farmers. A key component of policy design is ensuring that scheme characteristics appeal to users in order to achieve high uptake. It is therefore necessary to have a good understanding of how the designed policies satisfy stakeholders' needs in order to incentivise good biosecurity behaviours. This highlights the importance of gathering user experiences regarding their preferences for scheme characteristics and their motivations for contributing towards plant health. While the modelling exercises from the previous two chapters were useful to learn lessons about PPP design for cost and risk sharing, they lack direct application to existing PPPs. This chapter addresses this gap by focusing on a particular case study, and presents the results of an empirical project gathering farmers' preferences for different scheme characteristics. This work is undertaken while addressing my third research objective, which was to understand stakeholder's preferences for a PPP which incorporates a cost-sharing element within a risk sharing framework.

I decided to focus on comprehensive insurance products based on subsidised public–private partnership as these can offer signatories the flexibility to face common and novel risks while encouraging risk prevention efforts. The Spanish crop insurance system, Agroseguro, is an example of a current subsidised PPP based on joint participation between public and private institutions. It is considered one of the most advanced crop insurance systems in the EU and is voluntary. Currently, agricultural, livestock, forestry, and aquaculture production are covered against most of the climate risks that may affect them. However, damages from pests and diseases for crops are not covered. Using the ongoing struggles to eradicate a recently introduced potato pest in northern Spain, *Tecia solanivora,* I capitalise on this opportunity to gather data to assist in the design of new insurance policies to manage comprehensive multi-peril risks and encourage biosecurity efforts.

In particular, this study aims to understand crop producers' preferences for subsidised agricultural insurance characteristics as an instrument to manage risks from pests and diseases by conducting a choice experiment to evaluate grower's willingness to pay for different crop insurance products in Spain. Ultimately, the chapter finds that there is not a strong demand for crop insurance. However, from a policy perspective, I find that the insurance system could be used to encourage certain biosecurity practices among farmers, and as a prerequisite for extraordinary *ad hoc* compensation payments. I highlight the importance of making policies better serve the needs of farmers by, for example, partially subsidising national systems, developing more flexible policies and linking crop insurance to eligibility for disaster relief government payments, such as catastrophic compensation for damages from a quarantine outbreak. Lastly, I emphasise the value of agricultural insurance from a biosecurity policy perspective, since insured farmers are more likely to report outbreaks without delays, which may allow for rapid action and reduce the spread of pests and diseases.

This paper was written in the style of Journal of Risk and Insurance, to which it was submitted for publication.

I declare that the work submitted is my own. The contribution of co-authors is as follows:
Dr. Julia Touza: Supervision, review and editing.

Dr. Mario Soliño: Supervision of choice experiment design, review and editing.

UNDERSTANDING STAKEHOLDER PARTICIPATION IN PUBLIC-PRIVATE INSURANCE SCHEMES FOR PEST MANAGEMENT

4.2 Abstract

The recent intensity and frequency of catastrophic pest and disease outbreaks requires new agricultural risk management tools, in particular moving away from post-catastrophic relief compensation schemes. Comprehensive insurance products based on a subsidised public–private partnership can offer crop producers the flexibility needed to face common and novel risks while encouraging risk prevention efforts. The goal of this paper is to understand crop producers' preferences for agricultural insurance as an instrument to manage risks from pests, and identify the necessary scheme attributes to increase uptake of insurance products. We developed a choice experiment to evaluate "hard to reach" grower's willingness to pay for different crop insurance products in Spain. We find that while there is not a strong demand for crop insurance, from a policy perspective, the insurance system could be used to encourage farmers to use certain biosecurity practices, and as a prerequisite for extraordinary *ad hoc* compensation payments.

4.3 Introduction

Agricultural producers face many risks including uncertain weather conditions, crop diseases and pest outbreaks, price volatility and policy changes (Mercadé et al., 2009; Reyes et al., 2017). In particular, pest outbreaks, epidemics, and uncontrolled invasive species can result in extensive losses for both governments and farmers, such as economic costs to farmers, impacts on ecosystem functions, human health impacts, and knock on effects on trade relations disrupting entire economic sectors (Bielza Diaz-Caneja et al., 2009; Pimental et al., 2001; Simberloff et al., 2005; CBD, 2013; Pejchar & Mooney, 2009). Farmers tend to be aware of common and recurrent risks, but they underestimate the likelihood and severity of extreme events with potentially catastrophic consequences, such as a rare quarantine pest outbreaks (European Commission, 2018). This tendency to underestimate catastrophic events may make farmers unwilling to protect themselves (Wright and Hewitt, 1994). This is particularly problematic since the intensity and frequency of catastrophic pest and disease outbreaks is likely to increase due to climate change and other factors affecting the agricultural sector like trade liberalisation or production specialisation (Liesivaara & Myyrä, 2015; Perrings, 2016). Therefore, we should expect new risk management tools that deal with such adverse events would gain importance in coming years (Wenner, 2005).

Despite agricultural insurance having been around for centuries, European agricultural insurance markets are still not well developed, leaving governments and farmers depending almost solely on *ad hoc* relief payments (Diaz-Caneja et al., 2009; Garrido & Bielza, 2008). Catastrophic events, such as quarantine pest or alien species outbreaks, cause problems for insurance because they are systemic in nature and insurers face asymmetric information problems (Miranda & Glauber, 1997; Esuola et al., 2007). This means that those schemes often need support from the public sector to develop successful risk management strategies (Miranda & Glauber, 1997; Goodwin, 2001; Wright, 2014). Indeed, no private multi-peril insurance program has managed to subsist without government support (Wright, 2014). Comprehensive insurance products based on subsidised public–private partnerships can offer crop producers the flexibility to face common and novel risks, while encouraging risk prevention efforts (Iturrioz, 2009; Pérez-Blanco et al., 2014). Particularly, innovative public-private insurance schemes where costs and responsibilities of quarantine pest and disease outbreaks are shared among governments, industry, and farmers are increasingly appealing policies, in need of further exploration.

The goal of this study is to understand crop producers' preferences for subsidised agricultural insurance as an instrument to manage risks from pests and diseases while exploring novel cost sharing arrangements between the private and public sectors that may contribute to higher farmer engagement. We conducted a choice experiment to: 1) investigate the use of subsidised private-public insurance as an incentive policy to achieve higher biosecurity through requiring certain production practices; 2) study "hard to reach" farmers' preferences and willingness to pay (WTP) for subsidised private-public crop insurance to address the issues of insurance penetration and to dissuade ad-hoc compensation payments; 3) evaluate the demand for comprehensive coverage insurance products by considering crop insurance policies covering climatic risks, recurrent pest risks, and emergent pest risks, coverages currently not offered in Spain.

Despite information about potential demand for novel insurance products being crucial for the development of attractive products to farmers, European empirical studies on this topic are rare (some exceptions are Mercadé et al. (2009) and Liesivaara & Myyrä (2014)). Existing literature about demand for crop insurance has mostly focused on farm characteristics as factors that may affect insurance purchases, omitting farmers' preferences for scheme characteristics (one exception is Mercadé et al., 2009). Part of our contribution is to fill this gap. We do not consider insurance companies' ability to provide affordable policies, but rather focus on evaluating if a latent demand for alternative crop insurance products for emerging pests and diseases exists and, if so, how cost sharing strategies may incentivise farmers to engage in more biosecure practices.

4.3 Elements of a novel subsidised crop insurance product

One of the challenges faced by current EU agricultural insurance schemes is that insurance uptake has generally either been low (<10%) or fairly high (>70%) (Heikkilä et al., 2016). In the cases of high penetration it has often been achieved by making it compulsory or through group insurance (Heikkilä et al., 2016). Different reasons have been proposed to explain the low participation ratio, such as low risk perception, risk diversification, novelty of a new type of insurance, insurance cost or crop damage assessment rules, a general lack of insurance culture, or a limited understanding of insurance benefits, policy exclusions and coverage limitation, lack of awareness and understanding of insurance in risk management, and high administrative costs (Mercadé et al., 2009; Mahul & Stutley, 2010; OECD, 2011; Reynaud et al., 2018). Some studies noted that farmers' behaviour often does not conform to theory and thus it is crucial to better understand farmers' preferences in order to design policies that satisfy their needs (Moreddu, 2000; OECD, 2011; Meuwissen et al., 2001; McCarthy, 1998). In this section we introduce three novel insurance components that could deliver higher biosecurity while modulating the need for *ad hoc* compensation payments and increasing farmer insurance uptake.

4.3.1 Public-private element

While agricultural insurance markets originated over 200 years ago in Europe, only in the last few decades there has been a significant expansion in the range and scope of insurance products available to producers, mostly due to an increase in government support (Smith & Glauber, 2012). Insurances based on subsidised public–private partnership (PPP) can be supported through crop insurance premium subsidies and/or free reinsurance. Subsidising insurance has many advantages. For example, insurance provides farmers with a deed to receive compensation compared to government ad-hoc payments. It also provides faster payments, with receipt of payment after around 2 months on average while ad-hoc aid can take years (Bielza Diaz-Caneja et al., 2009). It is also a way to stabilise the budgetary impact on the public sector because the risk is transferred to private insurers, and to provide farmers a means to manage their own risk management strategies (Wright, 2014; OECD, 2011; Pérez-Blanco et al., 2014). Subsidised insurance products can be used as tools to mandate certain production practices that increase overall biosecurity (Santeramo & Ramsey, 2017). For example, the government can offer additional subsidies on the insurance premium for those producers that engage in growing practices that help reduce plant health risk, thus effectively becoming an incentive-based policy that enables a consistent and coordinated approach to reduce risks and costs in the long run (Waage et al., 2007).

EU’s crop insurance schemes are included in the second pillar of the CAP, meaning that member states have the option of subsidising up to 65% of the premium for agricultural insurances provided by private insurance companies or farmers’ mutual funds (European Commission, 2013; Liesivara & Myyrä, 2017). Despite the growing interest towards subsidised insurance schemes in Europe, the creation of such programs and the success of existing ones have remained limited, and specially covering pest and disease related perils. In some member states, insurance schemes for livestock production have been created, but the market for agricultural crop insurance is at an even earlier stage (Bielza Diaz-Caneja et al., 2009; Garrido & Zilberman, 2008; European Commission, 2018). Governments and crop producers have mostly relied on disaster relief payments and schemes fully funded by taxpayers, with *ad hoc* compensations amounting to about 1 billion per year in Europe (Bielza Diaz-Caneja et al., 2009; Garrido & Bielza, 2008). However, the emphasis is moving from government-run programmes and post disaster relief to insurance based on subsidised public–private partnership (Liesivaara & Myyrä, 2017).

4.3.2 Asymmetric information and crowding-out effects

Robust insurance schemes need to avoid moral hazard and adverse selection problems (Wright, 2014; Esuola et al., 2007; Liesivaara & Myyrä, 2017; Iturrioz, 2009). Moral hazard refers to a situation in which farmers take more risks after purchasing crop insurance. Adverse selection may occur if growers have more information about their likelihood of crop loss than insurers. Thus, high-risk farmers end up over-purchasing crop insurance, whereas low risk farmers under-purchase insurance. There are different ways to minimise these asymmetric information failures. For example, designing compensation payments based on indices over which individual famers have no influence, requiring to insure all fields with the same crop, and imposing deductibles are some methods to lessen moral hazard or adverse selection problems (Liesivaara & Myyrä, 2015; OECD, 2011; Čolović & Petrović, 2014). Offering subsidies can also help mitigate the problems of adverse selection, by attracting a large proportion of the population (Wright, 2014).

Liesivaara & Myyrä (2017) however argue that one of the main challenges of developing new crop insurance products is not necessarily moral hazard or adverse selection but whether crop insurance is viable under the availability of *ad hoc* disaster relief. Cafiero et al. (2007) propose that government support for insurance premiums is justified only if demand for insurance exists and private markets are not capable of providing producers with affordable policies. Otherwise, if compensatory assistance is provided, markets can be crowded out (Liesivaara & Myyrä, 2017; Meuwissen et al., 2003). One of the problems of the US agricultural insurance system is that, even with strong subsidisation, insurance failed to eliminate disaster payments, which average close to 1 billion dollars per year (Wright, 2014; Santeramo & Ramsey, 2017). Thus, a subsidised program's main challenge is to ensure that it deters ex-post assistance. One alternative is to associate eligibility to *ad hoc* payments to the purchase of agricultural insurance. This achieves synergies as insurance acts as the benchmark for triggering the extraordinary *ad hoc* measures, while providing additional incentives to purchase insurance (OECD, 2011).

4.3.3 Comprehensive coverage

In general, insurance policies are either specific peril products, multi-peril, or index-based products (Iturrioz, 2009). Specific peril products provide coverage against a farm's losses from a clearly specified peril. These types of policies are usually offered by private insurance companies (Smith & Glauber, 2012). Multiple peril products offer coverage against a farmer's crop losses from many risks. Yield products provide indemnities only when yields fall short of their trigger levels and value losses at a price determined when the farmer signs up for coverage (OECD, 2011; Smith & Glauber, 2012).

In the US, where insurance systems are more developed, there is no risk-specific insurance but instead yield insurance covers several risks, including revenue and income insurances (Santeramo & Ramsey, 2017). The US Multiple Peril Crop Insurance (MPCI) includes yield losses by pests and diseases, with damages calculated as the difference between guaranteed and actual yield. This partially explains how in the USA about 45% of field crops production value is insured while it is only 23% in the EU; however, the average premium rate is near 9%, and much higher than in Europe (4%) mostly due to their wider coverage (Civic Consulting, 2006). Currently most available insurance products in Europe are either single-peril or multi-peril, but only cover specific risks. Thus, there is a need to design new insurance schemes that offer the flexibility and comprehensive coverage needed by producers (European Commission, 2018).

4.4 Case study: Crop insurance in Spain

Agricultural insurance in Spain, founded in 1978, is an example of subsidised PPP, based on joint participation between public and private institutions. It is considered one of the most advanced crop insurance systems in the EU (OECD, 2011). It is voluntary, and private insurance companies' participation is achieved through a coinsurance pooling scheme: insurance companies market the policies, and the state insurance agency subsidises the premium and provides reinsurance. The State

Entity for Agricultural Insurance (ENESA), an autonomous body linked to the Ministry of the Environment and Rural and Marine Affairs (MAPAMA), acts as the policymaking body. ENESA creates the Annual Plan of Agricultural Insurance Policies, approved by the government, to determine the level of subsidies and to establish the technical conditions of insurance policies. Agroseguro is a private company owned by private insurers who participate in the scheme, in charge of administering the insurance policies and claims and conducting the statistical and actuarial research. Farmers pay Agroseguro the net of the insurance subsidy, and Agroseguro receives the subsidy directly from ENESA and the regional governments.

Since the insurance program has been established, farmers cover between 55%-35% of the insurance premium, and autonomous communities in some years subsidise up to near 20% of the cost of insurance; the rest is subsidised by Agroseguro (Agroseguro, 2015). However, despite the high subsidisation, the total liability of crop insurance is still roughly 35% of the total insurable agricultural output (Table 1), and the size of the program is still modest compared to the total economic size of the sector (OECD, 2011). It is important to note that this hybrid insurance market has not eliminated *ad hoc* ex-post assistance, but it has limited its scope (OECD, 2011).

Table 4.1 Spanish crop insurance numbers (Source: Agroseguro (2015), page 83)

	2017	**2016**	**2015**
Number of insurance policies	14,402	14,473	13,243
Cultivated area (ha)	433,996	435,095	428,769
Insured area (ha)	140,349	133,346	115,093
% insured area/cultivated area	32.34%	30.65%	26.84%
Insurable production	16,827,011	16,847,340	16,544,830
Insured production	6123,390	5797,937	4987,672
% insured production/insurable	36.39%	34.41%	30.15%
Total production value (millions €)	2191.43	2112.41	1840.99

Currently, agricultural, livestock, forestry, and aquaculture production are covered against most of the climate risks that may affect them[17]. However, damages from pests and diseases for crops are not covered. Using the ongoing struggles to eradicate a recently introduced potato pest, *Tecia solanivora*, in northern Spain (EPPO, 2015), we hope to utilise the opportunity to gather data, which will assist in the design of new insurance policies to manage comprehensive multi-peril risks.

The case study was targeted to crop producers in the region of Galicia, Northwest Spain. The reason for concentrating in a particular regional jurisdiction was due to the fact that the structure of insurance subsidised payments is partly determined at that level, as well as the creation of ad-hoc compensation

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[17] https://agroseguro.es/

payments. In Galicia, only 2% of the cultivated area is currently insured, making it the region with the lowest percentage of insured cultivated area in the country, despite having strong agro-economic sectors (Agroseguro, 2015). The area is mostly rural, with many farmers characterised as "hard to reach" due to remote location, old age, and limited educational background (Rodriguez-Couso et al., 2006). Many farmers in the region practice multi cropping and have relatively small holdings. Currently available insurance policies are often not designed with this consumer types in mind and, in order to enhance small farm participation in insurance, there is a need to better understand their needs (European Commission, 2018). It has the additional benefit that, by focusing on an area where a rare but potentially very damaging outbreak is occurring, respondents would, in principle, be aware of such extreme risks and not underestimate them.

4.5 Methods

Farmers' decisions to purchase an insurance scheme can be explained by the characteristics (or attributes) of the policies available and by farm and farmers' characteristics (Beharry-Borg et al., 2012; Ruto & Garrod, 2009; Espinosa-Goded et al., 2010). A farmer's decision to choose a contract is determined by the relative utility he can gain by choosing one contract (characterised by its attributes) compared to alternative policies available and choosing no contract. Data were collected using a choice experiment (CE) to elicit farmers' preferences, then combined with a questionnaire about their insurance and risk preferences. One advantage of CE is that it is possible to value changes in goods that do not exist (Bateman et al., 2002; Johnston et al., 2017). Because there are no available crop insurance markets that offer coverage for pest and disease risks in Spain, we relied on hypothetical products instead of actuarial data.

4.5.1 Attributes and levels

Each choice alternative consisted of 5 attributes: *coverage*, *production requirements*, *deductible*, *government co-payment option* and *insurance premium*. The attributes and their levels are partially based on Heikkilä et al. (2016), Liesivaara & Myyrä (2014), Civic Consulting (2006), and van Asseldonk et al. (2006). The levels of the attributes and the attribute combinations (and therefore the products offered) are hypothetical; however, they were all set at realistic ranges, drawing on the above literature reviews of European insurance systems and similarities to existing insurance products. The description of the attributes and levels is included in Table 4.2.

Table 4.2 Description of attributes and levels

<table>
<tr><th>ATTRIBUTE</th><th colspan="2">LEVELS</th><th>TYPE</th><th>CODE</th></tr>
<tr><td rowspan="2">Production requirements</td><td colspan="2">Standard: the insurance program requires production practices as currently specified in the Official State Journal (BOE)</td><td>Dummy</td><td><i>Base category</i></td></tr>
<tr><td colspan="2">Additional: the insurance program requires additional production practices for risk reduction. In particular, it requires compliance with the measures established in the technical standards of integrated production or specified requirements of plant health groups. This implies that production will be subject to regular controls and must keep records of all prevention and control measures taken. In addition, the use of certified seeds and a register for product traceability is mandatory. The producer will also be required to take a training course every three years, in which subjects of plant health, biological threats, and production methods of integrated control will be taught.</td><td>Dummy</td><td><i>Addit</i></td></tr>
<tr><td rowspan="3">Coverage</td><td colspan="2">Basic coverage: The risks covered are climatic adversities (hail, frost, persistent rain, flooding, high wind and fire) and damages cause by wild animals</td><td>Dummy</td><td><i>BC</i></td></tr>
<tr><td colspan="2">Medium coverage: This option includes all risks covered under basic coverage and damages caused to the production and quality of the crops due to plagues, diseases, virology, and pests that are recurrent.</td><td>Dummy</td><td><i>Base category</i></td></tr>
<tr><td colspan="2">High coverage: This option includes all risks covered under medium coverage and compensation for damages caused by quarantine pests, alien species, and emerging diseases and pathologies that require periods of production prohibition or destruction and removal of the plantation and product, as established in national eradication and containment plans.</td><td>Dummy</td><td><i>HC</i></td></tr>
<tr><td>Deductible</td><td colspan="2">Deductible levels of 10%, 20%, 30%</td><td>Continuous</td><td><i>Deduct</i></td></tr>
<tr><td rowspan="3">Government co-payment</td><td rowspan="3">Government covers the deductible amount in catastrophic events</td><td>Co-payment paid within 2 months</td><td>Dummy</td><td><i>Copay2</i></td></tr>
<tr><td>Co-payment paid within 6 months</td><td>Dummy</td><td><i>Copay6</i></td></tr>
<tr><td>No government co-payment</td><td>Dummy</td><td><i>Base category</i></td></tr>
<tr><td>Price</td><td colspan="2">14 €/ha; 28 €/ha; 42 €/ha; 56 €/ha; 70 €/ha; 84 €/ha</td><td>Continuous</td><td><i>Price</i></td></tr>
</table>

An insurance scheme should incentivise producers that purchase insurance to take risk prevention measures thereafter. The attribute "*production requirements*" evaluates the tradeoffs faced by farmers on biosecurity risk reduction efforts. Thus, some producers may wish to have a lower insurance premium in return for adopting costly enhanced biosecurity measures compared with the national standard, or vice versa.

Another insurance characteristic is the "*level of coverage*" that the insurance product provides. Increasing the coverage raises the premiums, but it may also provide a better safety net for farmers. Previous studies concluded that farmers are often not willing to purchase insurance that covers extensive losses (van Asseldonk et al., 2006). In order to explore preferences for comprehensive insurance, in particular that which also offers coverage against pest and diseases, we identified three incremental levels of coverage (Table 4.2).

The "*deductible*" is the minimum percentage of the loss in production value required to take a claim into consideration. It is a crucial part of insurance schemes, as it reduces moral hazard and incentivises disease prevention and good practices by growers. In current crop insurance products, this percentage depends on the insurance line and the type of risk, but it is often set at 30% (Mercadé et al., 2009).

Government participation in crop insurance is described through two mechanisms: the already subsidised premium amounts, and a cost sharing element where the public sector offers an additional payment to cover the deductible amount of those insured during catastrophic events (including climate related catastrophes or pests or diseases of great risk and that require special control measures, such as quarantine outbreaks) within a specified period (2 months or 6 months, see Table 4.2). By including a "*co-payment"*, the insured farmers would have comprehensive coverage during catastrophic events, but the total costs would be shared among the government, the private sector and farmers.

The "*insurance premium*" determines the annual amount that a farmer pays to the insurance provider for the production insured (price is set as the amount paid per hectare insured). When the insurance is fairly priced, risk averse producers should insure. Factors affecting the level of premium rates often include the frequency of risks in time and on area, the type of risk and the number of risks covered, the sensitiveness of crops, the number of farms insured, bonuses and subsidies, and other technicalities (Bielza Diaz-Caneja et al., 2009). Thus, in this context, since it is not possible to obtain real prices for the choice alternatives, we have considered as a starting point the crop insurance premium paid in the area of study[18]. The premiums displayed below represent the final cost to the farmers, after the government applied a subsidy[19].

4.5.2 Construction of the choice set

The experimental design was based on a B-efficient design (Olsen & Meyerhoff, 2016) with restrictions so that high coverage choice alternatives must have higher prices than those that offer lower coverage - a requirement for actuarial fairness. We used the NGENE software and each farmer was presented with 6 choice cards to avoid respondent's fatigue. Each choice card consisted of four alternatives (three insurance products and an option of no insurance). An example of a choice card is shown in Figure 4.1. A ranking experiment using a best-worst approach was employed, but only the best ranks were used for the analysis as suggested by Caparrós et al. (2008), Scarpa et al. (2011), Akaichi et al. (2013) or Varela et al. (2014), among others.

Figure 4.1 Example of a choice card

PROGRAM CHARACTERISTICS	**INSURANCE A**	**INSURANCE B**	**INSURANCE C**	**NONE**
Level of risk of coverage	Basic	Medium	High	☐
Production requirements	Additional	Standard	Additional	
Deductible	30%	10%	20%	
Government co-payment (during catastrophic events)	Payment within 2 months	Payment within 6 months	Payment within 2 months	
Price	14 €/ha	42 €/ha	56 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

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[18] We would like to thank Melisanto Sociedade Cooperativa, Ramon Mato Sánchez, Javier Rodríguez Sánchez, Adolfo Leiva Quintela, Ganadería Fisteus y Bolaño SC, A Carpaceira de Campos SC, Pedro Martínez Escalona, and Santiago Ruiz Suso for providing us examples of insurance policies.

[19] The motivation for including only the post-subsidised premium was due to following the current procedures used in insurance products in Spain, and thus to avoid respondent's confusion and easiness during the CE.

4.5.2 Questionnaire design and sampling strategy

In addition to the described choice experiment, we also surveyed respondents' experience with crop insurance products by asking their awareness of currently available insurance products, whether they had purchased crop insurance in the past, and their general satisfaction with insurance products available to them. Moreover, we also surveyed whether they had experience important economic losses due to pests and diseases in the past, whether they invest in biosecurity efforts, and their general risk preference. Lastly, we measured subjective risk perceptions by asking each respondent their beliefs about the likelihood of future economically important pest outbreaks in their crops, as well as their past experience with crop loss.

A pilot version of the questionnaire was distributed among producers as well as agricultural academics, insurance experts, agricultural cooperative managers, and policy advisers. Modifications were made following suggestions from the experts and farmers. In particular, the questionnaire was shortened to avoid respondent exhaustion and clarifications were added to the text.

Due to the inexistence of a dataset of active crop producers in the area, potential participants were identified through local agricultural cooperatives and agricultural groups. Agricultural organisations were contacted through email and invited to forward the questionnaire to associated members of their group to participate in the choice experiment. Because the study area is rural and the sample population was anticipated to be inexperienced with online questionnaires, data collection was complemented with face-to-face surveys over a period of three weeks. Main agricultural cooperatives and vegetable collection centres were identified and permission was requested to invite participants during the designated office hours. Participants who still preferred to complete the questionnaire at a more convenient time were forwarded the online version.

At the beginning of the data collection process, potential respondents were presented with a summary of the project detailing the objectives of the work as well as background information regarding current insurance products and mandatory requirements during pest outbreaks. They were also given a consent form, outlining that they agree to take part of the study and emphasising the voluntary and confidential nature of the questionnaire. While contingent valuation methods have been subject to criticisms, particularly regarding the validity of the results due to the hypothetical nature of the experiments, the hypothetical bias is expected to be low in this study (List & Gallet, 2001; Murphy et al., 2004)[20].

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[20] Studies have found that the magnitude of hypothetical bias is statistically less for willingness to pay (WTP) as compared to willingness-to-accept (WTA), for private compared to public goods, and that a choice-based method reduces the bias. Moreover, most farmers were expected to have experience with insurance products.

4.5.3 Statistical analysis

Eliciting preferences through a choice experiment is based on the assumption that a respondent maximises his utility through their choices over the alternatives presented (Train, 2009). Random parameters logit (RPL), also known as the mixed logit model, is a commonly used model to analyse choice data because of its flexibility to represent a range of respondents' behaviours. This model assumes that the unobserved utility of a crop insurance program j can be split into two components: a deterministic one expressed by an indirect utility function, V, and a random error term e. V is a function of the attributes of the alternatives and a set of unknown parameters to be estimated, and e captures unobservable factors that influence utility. Thus, the random utility gained by individual i from choosing insurance program *j* in a particular choice task *t* can be written as: $U_{ijt} = V_{ijt} + e_{ijt}$.

In specifying the random utility model, we address the issue of unobservable influences beyond attributes present in the choice sets by including an alternative specific constant (Hoyos, 2010). We further assume that the indirect utility derived from a crop insurance program is a linear function of all the program's attributes and of the alternative specific constant (ASC), which is coded as 1 when a program is presented and zero otherwise. We also included two interaction terms between price and the coverage attributes. The interaction terms represent the imposed restriction in the choice design that higher coverage products are more costly than low coverage products.

In our model, choice situations are characterised by attributes that can be best represented as a combination of categorical variables with several levels, and continuous variables. For the case of categorical variables, each attribute with L_K levels is modelled as a set of $(L_K - 1)$ dummies, where each dummy corresponds to one level of a categorical variable.

The specification of the indirect utility function becomes $V_{ijt} = \beta' x_{ijt}$, where x_{ijt} is the matrix of attribute levels (*ASC*, basic coverage (*BC*), high coverage (*HC*), additional measured (*addit*), deductible (*deduct*), government co-payment within 6 months (*copay6*), government co-payment within 2 months (*copay2*), price, and the interaction variables of price with coverage), and β is the vector of coefficients $(\rho, \alpha_1, \alpha_2, \gamma, \delta, \eta_{1,}, \eta_2, \psi, \lambda_1, \lambda_2)$.

$$V = \rho\, ASC + \alpha_1 BC + \alpha_2\, HC + \gamma addit\ + \delta\, deduct + \eta_1 copay6 + \eta_2 copay2 + \psi\, price + \lambda_1\, price * BC + \lambda_2\, price *\ HC \qquad (1)$$

Then, the probability for a choice is:

$$\Pr(y_{ij} = j) = \frac{\exp(\beta' x_{ijt})}{\sum_{q=1}^{J} \exp(\beta' x_{iqt})}. \qquad (2)$$

Since attributes are based on continuous and dummy variables and an income effect is not expected due to the design constraint that premiums depend on coverage levels (more coverage implies higher premiums), the implicit prices for each attribute is calculated as[21]

$$mWTP_{coeff} = \frac{\beta_{coeff}}{\exp(\psi)}. \qquad (3)$$

4.6 Results

4.6.1 Descriptive statistics

The survey was completed by 181 farmers. Some observations were deleted due to respondents being outside the case study area, or not being crop producers at the time the questionnaire was released. This was probably due to the sampling procedure reaching farmers outside the scope of the study. The final dataset included 142 respondents. While this number of respondents is lower than desired, it is similar with other landowner studies in rural areas and with hard to reach communities (Vaissière et al., 2018; Aslam et al., 2017). Because agricultural census data in Spain is not available, the true population size is unknown and thus it presents a difficult challenge to robustly assess whether the final sample size is appropriate. In these cases, a power analysis from trial data could be used to determine the sample size required to estimate coefficients for statistical significance. This was not possible with the small and heterogeneous number of respondents during the trial.

A summary of the demographic descriptive statistics of the respondents is included in Table 4.3. We also surveyed respondents' experience with crop insurance products by asking their awareness of currently available insurance products, whether they had purchased crop insurance in the past, and their general satisfaction with insurance products available to them. Moreover, we also surveyed whether they had experience important economic losses due to pests and diseases in the past, whether

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[21] If the price coefficient is distributed lognormal, and the coefficients of non-price attributes are normal then, the WTP is the ratio of a normal term to a lognormal term.

they invest in biosecurity efforts, and general risk preference questions. It is important to note that it is not possible to compare these statistics with the real population due to data unavailability.

Table 4.3 Summary of demographic statistics

DEMOGRAPHIC AND FARM CHARACTERISTICS	**LEVEL**	***% OF SAMPLE***
Gender	Female	43%
	Male	57%
Age	Under 30 yrs	4.93%
	30-50 yrs	52.11%
	Over 50 yrs	38.03%
Education	No education	2.11%
	Primary	32.39%
	Secondary	38.03%
	Higher education	27.46%
Percentage of household income derived from crop agricultural production	<5%	9.86%
	5-35%	30.28%
	35-65%	37.46%
	>65%	27.46%
	No answer / don’t know	4.93%
Agricultural cooperative member	Yes	54%
	No	46%
Total farm size	Average	8.4 hectares
	Largest	70 hectares
	Smallest	0.1 hectares
Cultivated area with vegetables	Average	4.46 hectares
INSURANCE EXPERIENCE AND OPINIONS		
Have you purchased agricultural insurance in the past?	Yes	25%
	No	75%
Self-assessed knowledge of agricultural insurance in Spain	Poor	66.9%
	Some	27.46%
	Good	5.63%
Satisfaction with current insurance products	Satisfied	9.86%
	Neither satisfied nor unsatisfied	57.75%
	Unsatisfied	32.39%
Should crop insurance be mandatory?	Yes	49%
	No	51%
Is insurance is a better risk management mechanism than *ad hoc* compensation payments?	Yes	76%
	No	24%

RISK PERCEPTIONS		
Self-identified risk behaviour[22]	Risk averse	22.53%
	Risk neutral	40.14%
	Risk prone	37.32%
Have you suffered losses over 30% of total production to pests/diseases in the last 5 years?	Yes	57%
	No	43%
Do you think that you will suffer losses over 30% of total production to pests/diseases in the next 5 years?	Yes	68%
	No	32%
How often do you conduct biosecurity efforts?	Seldom	3.52%
	Sometimes	16.90%
	Often	29.58%
	Always	50%
Do you think you should be compensated for those biosecurity efforts?	No	14.79%
	Yes, partially	35.92%
	Yes, totally	24.65%
	Yes, over compensate	24.65%

Most farmers had not purchased insurance in the past and claimed to have little knowledge of insurance products available to them. Only under 10% of the respondents are satisfied with current insurance programs offered. Those who are unsatisfied cite “main risks not covered”, followed by “compensation payments too low” as the main reasons for their dissatisfaction. When asked for suggestions for improving agricultural insurance, the most common response was for insurance products to cover more risks, followed by providing more information and workshops on how insurance products work, and an increase in government subsidies in order to/ so as to lower the cost to farmers. While crop insurance is voluntary in Spain, roughly half of the respondents claimed that crop insurance should be made mandatory, and over 75% believe that insurance is a better risk management mechanism than *ad hoc* compensation payments.

On average, our sample self-identified as risk-prone. In terms of respondents’ past experiences with pest, 57% claimed to have suffered important losses and 68% believed that they will experience substantial economic losses due to pests in the future. It is not surprising that a higher proportion of farmers expect to be impacted by damaging pest outbreaks in the near future given the recent increase of quarantine outbreaks in Spain in recent years and their widespread media coverage[23]. Participants were also asked to evaluate the perceived impact of different risks on their crop production, and the

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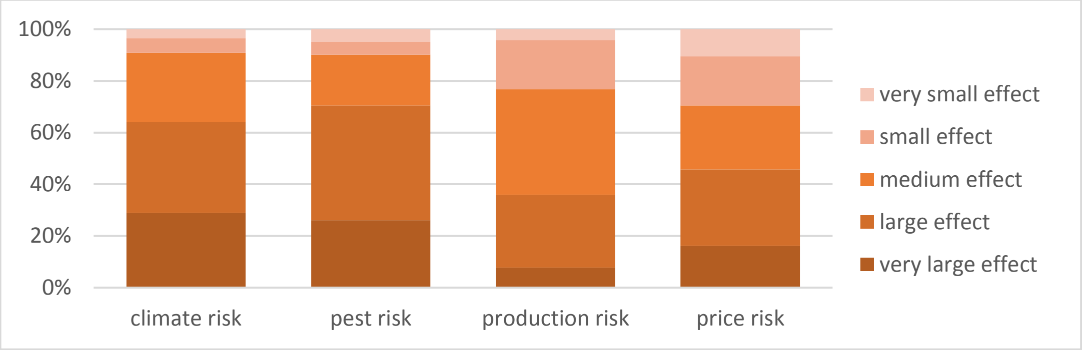
[22] We measured risk preferences by asking participants if they considered that their farm management style was more or less risky than the average neighbouring farmer.

[23] El Pais, 2017., https://elpais.com/elpais/2018/06/25/ciencia/1529910226_926555.html

results are included in Figure 4.2. Climate related events and pests and diseases were both perceived to potentially have large or very large impacts on next year's crop production.

Figure 4.2 Respondents' perceived potential effects of different risks on crop production



Almost 70% of the respondents claimed that they always or often conduct biosecurity efforts to prevent and control the spread of pests and diseases in their crops, such as destroying infected crops, using pesticides, using certified seeds, etc. To the question "Do you think you should be compensated for those efforts", 14.79% claimed that they shouldn't receive compensation because it is the grower's responsibility to manage pest risks; 35.92% answered that they should be partially compensated for the costs of biosecurity controls; 24.65% thought that farmers deserve to get full compensation; and 24.65% thought that they should be compensated in full and receive additional funds because their prevention and control efforts would avoid costs to others.

4.6.2 Empirical results

As discussed previously, each farmer had to complete 6 choice sets, with each choice set consisting of 4 options (three insurance products and no insurance). In 95.4% of cases, participants chose an insurance programme. This level of preference for insurance products, while unusual in this type of choice experiments (Scarpa et al., 2011), can be explained by the current dissatisfaction with the limited number of insurance products available, in terms of risks and crops covered.

We estimated a number of models over respondent choices, including multinomial logit, latent class models, and different models that include interactions of demographic, attitudinal and behavioural variables with attributes. Both normal and lognormal forms of distribution were tested for the insurance attributes as well[24]. The best statistical fit and most parsimonious model was found to be a RPL with attributes, interaction terms between the price and coverage attributes, and a non-random ASC. The model assumes a normal distribution for all attributes except for the premium, which follows a lognormal distribution. The results in Table 4.4 include the values for of the random parameters logit coefficients, their statistical significance, and the standard error. The McFadden pseudo R-squared for the RPL model was 0.316, i.e. higher than the minimum value recommended in the literature (Christie et al., 2007).

Table 4.4 Results of the Random Parameters Logit Model

RANDOM PARAMETERS LOGIT MODEL	COEFFICIENTS	STD. ERROR	Distns. of RPs. Std.Devs Coefficients	Distns. of RPs. Std.Devs Std. errs
Random parameters				
*Price*Basic*	-.07954**	.03132	.01041	.02276
*Price*High*	-.10398***	.02565	.00793	.00955
Basic	4.24693***	1.46255	2.12753***	.35760
High	5.04658***	1.66861	1.53020***	.37943
Additional	-1.10080***	.39352	1.08056***	.27849
Deductible	-.05942***	.02068	.10058***	.01757
Sharing6	1.46037***	.35215	.24269	.32593
Sharing2	1.77054***	.37646	.60503	.43560
Price	-2.19275***	.25388	1.13730***	.28562
Non-random parameters				
ASC	-2.96493**	1.23038		
McFadden Pseudo R-squared	.3156020			
Inf.Cr.AIC	1654.7			
Significance level	.00000			

Note: ***, **, * ==> Significance at 1%, 5%, 10%

The results are largely consistent with the anticipated relationships. The estimated coefficient for the ASC was negative and significant, meaning that there are some unidentified variables which induce farmers to prefer to not purchase any of the offered insurance products. These omitted variables might include other types of insurance conditions, but might also reflect a general reluctance to join insurance schemes, as previously mentioned. The positive coefficients for both coverage levels, basic and high, means that respondents prefer a basic or a full coverage, instead of the medium coverage.

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[24] With the normal distribution, some individuals will have negative coefficients and others positive, and the lognormal distribution is useful when the coefficient is known to have the same sign for every person, such as the price coefficient that is known to be negative for everyone in a mode choice situation (Train, 2009).

This can be due to farmers perceiving that it is not worth insuring against recurrent risks, maybe due to having other risk management mechanisms available at cheaper costs for the named perils under that insurance coverage, such as use of pesticides or crop rotation (Santeramo & Ramsey, 2017). Higher coverage is the preferred option, as evidenced by a significantly higher positive coefficient. Requiring additional production measures to increase crop health decreases the preference for insurance. Similarly, the higher the deductible percentage, the lower the likelihood that farmers would take an insurance contract. Offering government co-payments of the deductible amount during catastrophes increases the demand for insurance, especially if the payment is promised in a shorter period. The demand for crop insurance decreases with the insurance premium, as expected by the Law of Demand. The interaction of the coverage attribute with the prices represents the restriction we imposed on the choice experiment design to represent the general condition that insurance products that offer coverage against more risks carry higher premiums. The interaction terms are significant and negative. Thus, an increase in the premium for low or high coverage the demand decreases.

4.6.3 Welfare analysis

Economic interpretation of the results can be obtained from the implicit prices: the marginal rates of substitution between price and insurance attributes. These reveal how willing farmers are to trade one attribute for another. The results are included in Table 4.5. We also included the standard error for the mean values and the confidence intervals at 95% level. The standard errors were calculated using the Delta method (Greene, 2003).

Table 4.5 Implicit prices of insurance attributes

ATTRIBUTES	**mWTP**	***Sd mWTP***	***95% Confidence Interval***	
ASC	-26.57***	5.69657	-37.7303	-15.4001
*Price*Basic*	-0.71***	.16541	-1.03688	-.38847
*Price*High*	-0.93***	.17549	-1.27561	-.58771
Basic	38.05***	6.53922	25.2350	50.8683
High	45.22***	11.53056	22.6169	67.8158
Additional	-9.86***	2.95124	-15.64729	-4.07864
Deductible	-0.53**	.25640	-1.03490	-.02985
Sharing6	13.08***	2.74828	7.6981	18.4711
Sharing2	15.86***	3.86590	8.2867	23.4407

The negative WTP for the ASC represents farmers' preferences for no insurance. Farmers are willing to pay over 45€ per hectare for a more comprehensive coverage, and 38€ per hectare for a basic coverage that covers only climatic risks. They require a discount of 9.86€ per hectare if the insurance product requires additional production measures, such as certification requirements. The implicit price for the deductible describes farmers' preferences towards 1% changes in the deductible. Thus, for a 10% increase in the deductible, the implicit price is a deduction of 5.30€ per hectare. Lastly, if the government agrees to bear the deductible amount during catastrophic events, farmers are willing to pay 13.08€ per hectare more if the payment is promised within 6 months and 15.86€ per hectare if the payment is within 2 months from the time of the claim.

Because of the restriction in the design regarding the coverage and premiums, the total WTP for an insurance of certain coverage needs to account for the implicit price of the coverage amount as well as the effect of the interaction term. Interestingly, while farmers are willing to pay more for high coverage products, this result only holds for lower insurance premium amounts. This result is the direct effect of the restriction imposed and interaction between price and coverage, because the implicit price for the interaction term for high coverage is more negative than for basic coverage.

4.7 Discussion

In this paper we explored preferences for comprehensive crop insurance products based on private-public partnerships that offer farmers the flexibility to face common and novel pest and disease risks, while encouraging prevention efforts, and we identified the scheme attributes that would increase the uptake of insurance. We developed a choice experiment to evaluate grower's willingness to pay for different crop insurance products in Spain. Despite CE having been used in many research fields, including the estimation of consumer WTP for different products and in studies evaluating WTP for public goods, applications of CE to crop insurance are rare. A few examples exist, for example, Nganje et al. (2008) examined preferences for holistic crop and health insurance among US farmers; Mercadé et al. (2009) analysed Catalonian vegetable producers' preferences for crop insurance with CE; Liesivaara & Myyra (2017) used a choice experiment to evaluate the WTP of farmers to buy crop insurance in Finland; Ranganathan et al. (2016) conducted a choice experiment to explore the demand for price insurance for farmers in India. Thus, our analysis represents a contribution to the current literature on crop insurance demand modelling with CE data.

Insurance premiums and their subsidies are often key in determining the demand for insurance (Garrido & Zillbermann, 2008; Bielza et al., 2007). We found that farmers are not willing to pay substantially for crop insurance, a result in line with the literature (Smith & Glauber, 2012). As Hazell et al. (1986) mention, farmers are sometimes even unwilling to pay the full cost of all risk insurance or the actuarially fair premium rate. For example, Mercadé et al. (2009) found that if they estimated the WTP for vegetable insurance using levels similar to those currently in offer, the resulting willingness to pay is negative, which confirms the low rate of insurance participation. The low WTP values could be a latent connection with previously negative experiences with insurance products. We found the vast majority of respondents were unaware of or unsatisfied with policies currently offered. Interestingly, while the statistical results show limited demand for crop insurance, farmers agreed that insurance is a better mechanism than *ad hoc* catastrophic compensation. This issue was part recognised in the questionnaire, when roughly half of the producers stated that crop insurance should be made mandatory, presumably to force uptake in face of the low demand.

It seems that farmers do not recognise the worth of current crop insurance; however, alternative insurance products can be made more attractive to them. Respondents claimed that insurance products must be more flexible, affordable, and tailored to their needs. Concerning the "risks covered" attribute, insurance policies that offer either low, climate only, or full coverage, including quarantine pests and diseases, are preferred. Thus, moving away from specific peril insurance to comprehensive coverage can provide the flexibility that farmers require and thus improve insurance penetration (European Commission, 2018). This result is contrary to the findings of van Asseldonk et al. (2006). Moreover, the median WTP for farmers for a 10% increase in the deductible was -0.53 €/ha, lower than found in similar literature (Mercadé et al., 2009). While most offered insurance products in Spain require a 30% deductible (Agroseguro, 2015), it might be worth re-evaluating this condition in preference for a lower threshold of uncovered damages to make insurance products more suitable to farmers (Mercadé et al., 2009).

A main challenge of subsidised crop insurance is to ensure that the system deters ex-post assistance and is efficient in defining the boundaries of catastrophic risk (OECD, 2011). One approach could be linking the eligibility to *ad hoc* funds to the purchase of agricultural insurance. Linking government payments to the purchase of insurance through a co-payment in the eventuality of a catastrophic event can act as an additional incentive for uptake. We found that, when government catastrophic support is connected to insurance, farmers are willing to pay up to 15.86 €/ha insurance more for those policies. Other authors have also explored the boundaries of insurance and *ad hoc* payments. For example, contrary to Liesivaara & Myyrä (2017), who found that in order for a crop insurance market to develop, the government should either pay disaster relief payments or provide insurance premium subsidies but refrain from using both, we provide an alternative where it is possible to connect both.

We also explored the effects of requiring additional production measures for insurance purchase, such as requiring traceability of the seeds and vegetables and health certification that would increase biosecurity. Farmers require a decrease in insurance premium of 9.86€/ha if additional production constraints are required. Previous literature already mention the co-benefits of crop insurance, such as Reyes et al. (2017), who claim that crop insurance can even be a climate change mitigation and adaptation strategy since it can provide farmers with the risk management tools to invest in more risky and high value crops. For example, PCIC (the crop insurance program implemented in the Philippines) has dual objectives – enhancing access to credit, as well as managing risks from natural calamities, pest, and diseases (Reyes et al., 2017). It is important to note that from a biosecurity policy perspective, subsidised agricultural insurance can be also justified because insured farmers are more likely to report the incidence of infectious plants and diseases without delay because they will receive compensation for their losses (Goodwin & Vado, 2007). The early reporting of outbreaks also provides governments and the private sector with information about the spread and abundance of diseases for early and quick action, reducing the impact from diseases. Recognising the value of ancillary benefits adds significant value to crop insurance as a risk management tool for both farmers and governments (Santeramo & Ramsey, 2017; Mishra et al., 2005).

4.8 Conclusions

There is a consensus among insurance companies, governments, and farmers' associations that crop insurance markets tailored to different types of farms should exist and be promoted (European Commission, 2018). Public-private partnerships in agricultural insurance can lead to higher penetration, more accountability of risks and damages, improved financial performance, and deliver additional biosecurity benefits (Reyes et al., 2017). The main challenge for the Spanish subsidised system is to ensure its development within a changing policy environment and while modulating and lessening ex-post disaster assistance. Insurance products could be developed further to best serve the needs of farmers. In particular, partially subsidising national systems, expanding eligible risks covered for crops, developing more flexible and simplified policies, and providing more information could go a long way to increase "hard to reach" farmers' participation in insurance schemes. While the aim of this paper is not to evaluate the supply and actuarial fairness of the insurance policies, the article provides a foundation to stimulate further contributions that explore farmer's preferences for different risk management policies.

A secondary objective of crop insurance should be focused on promoting ancillary benefits. The adoption of crop insurance might be a catalyst for the entire market and thus decrease adverse selection. Crop insurance could be a prerequisite for eligibility for participation in government programs such as disaster relief, thus separating the role of catastrophic assistance and risk management subsidisation. Moreover, subsidised crop insurance can be used to encourage farmers to use certain biosecurity practices, thus helping reduce the adverse environmental consequences of agriculture and promote a culture of pest health by encouraging detection and early action.

Some final important remarks to consider are that once the government subsidises the insurance program, the private sector has incentives to lobby for increased subsidies to enhance their revenues and returns (Smith & Glauber, 2012). Any income transfer program that requires market interventions creates distortions in the markets, and crop insurance subsidies are no exception (Smith & Glauber, 2012). However, potential ancillary benefits from subsidised insurance, such as those mentioned previously, might justify the inefficiencies created. Another shortcoming of the study is the combination of data collection methods. While it is recommended to limit data collection to one collection method to avoid biases, due to the geography and demographics of respondents and the inexistence of a census, a mixture of methods was used to reach more farmers. Lastly, we acknowledge that the monetary values that farmers place on accepting different insurance conditions are specific to each case study. Thus, the results of this study need to be tested in other regions to verify the extent of their applicability.

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Chapter 5 - Discussion, policy implications and suggestions for future research.

5.1 Chapter summary

In this concluding chapter I briefly reiterate my overall aim and approach. Then, I identify key findings that cut across the papers that comprise the thesis and provide my critical reflections of the approaches used throughout the thesis. Next, I discuss opportunities for future research and highlight the significance of findings for policy impact and development.

5.2 Thesis aim and approach

This thesis explored how different types of private-public partnerships (PPPs) could be designed for effective for pest management, in particular focusing on how to incentivise private biosecurity efforts within such schemes. Three interconnected papers modelled key elements of PPPs: risk and responsibility sharing, cost-sharing, and private agent preferences for engagement within such schemes. The work showed the benefits of using pre-agreed cost and responsibility PPP to deliver a cost-effective approach to biosecurity. Furthermore, it provided a foundation to stimulate the application of novel methodologies to address the complexity of risk outbreaks and how it responds to agent interactions.

In Chapter 2 I analytically evaluated the role of contracts as an instrument in plant pest and disease management and provided a basis for understanding and capturing a key element of PPPs: risk and responsibility sharing through to the contractual nature of PPPs. The approach taken, a principal-agent framework, modelled a contractual relationship between the public sector and two private agents, where the government makes payments to the agents in order to compensate for private biosecurity actions while sharing the risk of pest outbreaks among all stakeholders. This chapter showed that the public sector could harness increased private biosecurity measures by structuring contingent payments to agents which depend both on their plant health outcomes and that of the other stakeholders.

Chapter 3 modelled cost-sharing strategies between the government and private agents to explore government support to incentivise private actions towards biosecurity by using a game theory approach. The paper emphasised the challenge in developing biosecurity policies based on compensation payments due to the fine line between payments effectively encouraging private efforts or distorting incentives due to overcompensation.

In Chapter 4, I designed a particular type of PPP which incorporated a cost-sharing element within a risk sharing framework, a subsidised public–private insurance that offered coverage to face common and novel risks while encouraging biosecurity efforts. This work allowed me to understand crop producers' preferences for agricultural insurance as an instrument to manage risks from pests and diseases, in particular for an insurance private-public policy scheme with both cost and responsibility sharing components. Results of this work support the importance of targeting insurance schemes to best serve the needs of farmers by, for example, partially subsidising national systems, expanding eligible risks covered for crops, developing more flexible and simplified policies, and linking crop insurance to eligibility for disaster relief government payments.

The main findings of this research are discussed further in this chapter, alongside the implications for plant health policy and biosecurity, especially in relation to informing the design of new collaborative and contingent public private partnership to manage pests and diseases.

5.3 Summary of main findings

The main contributions of this thesis may be grouped into categories as follows:

(a) *The public sector can harness increased private biosecurity by specifying contingent compensation payments to private agents prior to outbreaks*

The use of full compensation payments for disease and pest damages, particularly within animal health, has contributed to the view that ex-post, direct government support undermines efforts to control epidemics, and thus such instruments are often under scrutiny from regulators (Liesevaara & Myyrä, 2014). For example, it is often described that the use of compensation for damages was the reason why control efforts in the Foot and Mouth outbreak were not effective (Fraser, 2018; Hennessy & Wolf, 2018; NAO, 2002). While those type of payments have often been ineffective in the livestock industry, this thesis argues that direct government support may have a place within public plant and tree health policy, particularly to encourage private biosecurity efforts. This result is also supported within the plant health literature (Mumford, 2011; Bicknell, Wilen & Howitt, 1999, Olmstead & Rhode, 2015; Gramig, Horan & Wolf, 2009).

This thesis illustrated how compensation payments could be designed and structured to deliver public benefits, in terms of a reduction in the probability of outbreak and spreading the risk among stakeholders, while being a cost-effective policy for the government. However, compensation must be large enough to ensure the commitment of agents to biosecurity efforts but not too large as to discourage their incentives, as seen in Chapter 3 (see Figure 3.5) and pointed out by Hennessy and Wolf (2018). I found that pre-agreed compensation payments limited to partially covering the preventive biosecurity effort costs of scheme members can avoid the common reported adverse incentives of compensation (Figure 3.3).

In order for compensation payments to be effective, the structure of payments needs to avoid the emergence of moral hazard behaviours (Bremmer & Slobbe, 2011). For example, in Chapter 3 under Scenario B (Section 3.6.2), agents were prone to moral hazard. While government payments incentivised more private agents to join, their joint efforts translated into a reduction in the probability of an outbreak. Thus, the most cost-effective scheme structure only requires partial compensation, sharing the burden of outbreak damages between both agents and government. Moreover, in Chapter 2, I have shown that contracted payments can be designed to spread the economic risk across signatories (equations 12 and 13 pp. 42), by making payments to agents which depend both on their performance and that of the other stakeholders, making agents less inclined to engage in moral hazard.

In these collaborative ex-ante partnerships, it is crucial that all parties agree on who must bear the risks and responsibilities of managing an outbreak, and this can prove a difficult challenge (Bremmer & Slobbe, 2011; OECD, 2011). Alternatively, another method to dissuade the emergence of moral hazard is by splitting costs between the public and private agents, for example with the use of deductibles, as presented in Chapter 4. While the use of deductibles decreases the uptake of policies (Table 4.5), they are often described as a key element of a functioning insurance programme because they disincentivise moral hazard behaviours.

(b) Plant health policy must be tailored between pure and impure public goods

Plant health has public good characteristics, which can induce a strong incentive to free-ride on the management efforts of others (Graham et al., 2019; Perrings et al., 2002). This is particularly likely when there is large heterogeneity of stakeholder interests and a significant social character of the potential impacts on ecosystem services and human health (Donovan et al., 2013). This situation is particularly common with respect to certain tree pests and diseases since their effects may be less immediate and visible but may have profound impacts on the landscape in the long term (Waage & Mumford, 2008; Wilkinson et al., 2011). In these pure public good cases, I analytically show that PPPs are optimally designed by having the government cover most of the damage or effort costs (Figure 2.2 and Figure 3.7). The divide of costs weighted by social vs. industry impacts is also found in the literature (Waage, Mumford, Leach, Knight & Quinlan, 2007) and in policy (for example the division of costs of the EPPRD presented in the Introduction Section).

However, in addition to biosecurity efforts creating public benefits, for example by lowering the probability of the outbreak, biosecurity efforts may also generate ancillary or co-benefits (Pittel & Rubbelke, 2008). In this case, plant health efforts can be considered impure public goods (i.e.: agents benefit from their own biosecurity efforts as well as those of others (Sandler & Arce, 2002)). Ancillary benefits are exclusively enjoyed by individual agents who invest in biosecurity, such as indirect benefits from further awareness of risks along an agent's own supply chain, or direct benefits from a gain in the price premium on their more biosecure products (Fearne, 2000).

I found that in certain cases of impure public goods, government support in the form of compensation payments is not needed to encourage private biosecurity incentives. Both in Chapter 2 and 3 (Figure 2.2 and Figure 3.7), I illustrated that even small appropriation of ancillary benefits by agents can be sufficient to encourage investments in biosecurity. This result is consistent with Reeling and Horan (2015) who show that the coordination among agents depends on the relative endogeneity of risk, defined as the level at which private agents can take control of their own biosecurity risk. There is however, a role for the government in ensuring that co-benefits can be realised. For example, in Chapter 4, I found that subsidising agricultural insurance by linking post catastrophic payments to uptake can encourage farmers to insure their crops and thus incentivise the early reporting of pest and diseases. Evidence of these results can also be found in the policy arena. For example, the increasing pressure for governments to enforce biosecurity specifications within procurement rules has been highlighted as a key policy intervention that could act as a trailblazer for biosecurity uptake by industry (van Asselt, van der Grijp, & Oosterhuis, 2006; European Comission, 2011). Recognising the value of ancillary benefits adds significant value to pest management for both private agents and industry, and governments (Santeramo & Ford Ramsey, 2017; Goodwin & Vado, 2007; Mishra, Nimon & El-Osta, 2005).

(c) A cost and risk sharing approach can deliver increased biosecurity

As stated in the Introduction, a shared private-public approach to plant health can be an effective policy that achieves strategies towards biosecurity that otherwise might not be possible (Epanchin-Niell & Wilen, 2014; Liu & Sims, 2016; Waage et al., 2007). In Chapter 2, I found that a combined approach of government biosecurity efforts and post-outbreak incentives is the most cost- effective government policy to reduce the probability of outbreaks (Figure 3.5). Thus, there is the potential for lowering compensation payments and diverting part of those funds to conduct further government biosecurity efforts, such as inspections and pre-border checks. This result encapsulates a common theme across the literature on pest management regarding the importance of consistent and coordinated action in biosecurity (Jin & McCarl, 2006; Barnes, Moxey, Ahmadi & Borthwick, 2015).

However, it is crucial that both agents and governments understand the roles each party plays in order to avoid delayed action and under-provision or crowding-out of efforts (Bremmer & Slobbe, 2011;

OECD, 2013). Designing contractual relationships prior to outbreaks (as described in the timeline in Chapter 2, Figure 2.1) can ensure a clear split of responsibilities. Alternatively, as found in Chapter 4, another method to achieve public-private coordination was to link ex-ante government payments to the purchase of private insurance through a co-payment in the eventuality of a catastrophic event (Table 4.2). In this case, not only linking payment eligibility to private efforts reduces the need for ex-post damage compensation but it also encourages insurance uptake, thus illustrating an example of how policies could be designed incorporating both market and public instruments to deliver synergies in plant health. Lastly, while this thesis only explored 3 forms of PPPs, there is a need to develop and evaluate novel forms delivering a cost and responsibility sharing approach to plant health.

(d) It is crucial to have farmer engagement in the design of new policies so that new schemes can be made more attractive to users

Engaging all stakeholders is particularly critical in plant health, where market failures are prevalent (Mumford, 2011; Marzano, Dandy, Bayliss, Porth & Potter, 2015). Inclusive and participatory approaches to policy design as well as raising awareness about pests and diseases can increase the desire to participate or support management measures (Reed & Curzon, 2015; Mills et al., 2011). For example, previous stakeholder experiences with policies and regulation can act as a deterrent to uptake of new initiatives. In Chapter 4 I found low WTP values for insurance (see Table 4.5), which could be a latent connection with previously negative experiences with insurance products (Mercadé, Gil José, Kallas & Serra, 2009; Smith & Glauber, 2012). Moreover, in the Spanish case study I found that the vast majority of respondents were unaware or unsatisfied with insurance policies currently offered (Table 4.3). In order to develop successful new biosecurity policies, it is imperative to make schemes more attractive and tailored to the need of stakeholders; in this particular case by, for example, making insurance products more flexible, affordable and with full coverage.

However, while it is conventionally perceived that biosecurity schemes require high, or even full, uptake from private agents or industry to be an effective biosecurity policy (Sutcliffe, Quinn, Shannon, Glover & Dunn, 2018), in Chapter 3 I found that the most cost-effective scheme only requires partial participation from private agents (Figure 3.5). Thus, plant health policies which may only target or capture a segment of stakeholders may still be effective in contributing towards biosecurity. However, as mentioned above, those agents actively engaging in efforts, such as participation in voluntary schemes, must be rewarded to avoid free-riding, either through partial pre-agreed compensation for their efforts or by facilitating the appropriation of biosecurity benefits (Table 2.2, Figure 2.2, Figure 3.7), a result in line with the literature (HTA, 2019; Liu & Sims, 2016; Enright & Kao, 2015; Wilen, 2007).

5.4 Reflections on methods

This thesis was designed to explore PPPs from different theoretical frameworks, thus borrowing modelling elements from different fields in order to incorporate the complexity the research area. The interdisciplinarity of the work allowed me to better understand the potential strength and suitability of how these different modelling approaches can contribute to biosecurity. Therefore, this thesis's analysis and findings not only represent a contribution to plant health policy area, but also on how methodologies from other fields could be repurposed and useful when designing biosecurity PPPs.

Chapter 2 used a framework commonly used in contract theory, principal-agent modelling. In the last few decades, principal-agent models have received increased attention as important analytical methods to study the use of incentive schemes and contracts among agents, particularly in the design of agri-environmental payments (Fraser, 2015; Gómez-Limón, Gutiérrez-Martín, & Villanueva, 2019). Using a tiered optimisation problem allowed me to illustrate how payments could be optimally designed to provide a basis for the understanding of biosecurity roles and responsibilities by public and private agents to achieve socially desirable outcomes. The methodological novelty of Chapter 3 lies in the use of a standard coalition formation game from non-cooperative theory in order to quantify potential synergies of public and private biosecurity investments. In this case, while previous plant health literature has used game theory to model implications of agent interactions (Hennessy, 2008; Kleczkowski et al., 2018), less attention has been paid to how coalitions form. This literature was proven very useful to provide a foundation framework for modelling recent policy schemes, such as HTA's voluntary Plant Health Assurance Scheme. Lastly, in chapter 4 I turned to choice experiments to collect evidence of trade-offs between the attributes of the PPP scheme, from the user's perspective. Despite choice experiments having been used in many research fields, applications in plant health are less common (an exception is Sheremet, Healey, Quine, & Hanley, 2017) and, in particular, choice experiments to explore crop insurance are relatively rare with a few exceptions being Nganje, Hearne, Gustafson and Orth (2008), Mercadé et al. (2009), Liesivaara and Myyra (2014), and Ranganathan, Gaurav and Singh (2016). Thus, the analysis represents a contribution to the current literature on preferences for scheme characteristics and demand modelling with CE data.

However, it is important to note that the models developed in this thesis are not meant to provide a detailed description of real-world partnerships, but instead demonstrate the usefulness of such methodological approaches to inform the conceptualisation of PPPs. The objective was to encourage further discussions on the use of pre-emptive agreements to encourage private biosecurity actions and to provide clarity about the interactions between the government and private agents. Thus, the key element was whether the structure of the models is appropriate to capture the key underlying processes involved in the decision-making. This was achieved using parsimonious and stylised models that capture the most important generalisable interactions and underlying relationships.

An important aspect that needs consideration relates to parametrisation and validation of models in Chapter 2 and Chapter 3. The parameter values used in this thesis were based on a combination of previous literature and particularly selected to capture changes in behaviour, thus avoiding parameter combinations that produce inconsequential results. While it is preferred that models are calibrated with real world data in order for assumptions to be reasonable with respect to the real system, whether primary or secondary, there are significant obstacles to achieving this. Particular challenges are the paucity of data, the private nature of benefits and costs of agents and industry, difficulty in measuring risk behaviour and preferences, struggles in measuring plant health outcomes and, lastly, that the explored PPPs are currently untested.

Employing a mixed method approach, whereby parameter values come from primary data collection, such as choice experiments, which then feed into the theoretical models could solve the parametrisation challenge. However, each model and parameter type may require different empirical methods for data collection. For example, certain economic parameters could be captured using a choice experiment but this data collection method might not be suitable to gather biological parameters related to the spread of a pest. Moreover, the values derived are specific to each case study and the results need to be tested in other regions to verify the extent of their applicability, thus resulting in a resource intensive data collection process.

A last methodological reflection, specific to Chapter 4, relates to survey recruitment. As part of the research exercise with farmers, I had multiple observations that might be beneficial for future research. During the recruitment of farmers, I made use of social media, notably Facebook, as well as national and regional organisations to reach online farmer communities. While this approach was successful in engaging organisations, and generating interest in the research, it was unsuccessful as a recruitment tool and to engage with farmers themselves. Upon reflection, I found that with hard-to-reach groups such as small rural farmers, in person data collection is more appropriate (e.g. Aslam, Termansen & Fleskens 2017). While this approach is time consuming, it provided me an opportunity to explore farmer responses with more detail.

5.4 Reflections on the PhD journey and studies

This section provides a personal reflection of the PhD journey, providing an opportunity to reflect on the PhD journey, from reviewing what personally motivated me to carry out this research, how the thesis structure formed itself, and how my approach, skills and views of the subject changed over the years and as a result of my years of study.

The main research question emerged from the literature review, after learning about the challenges of coordinating pest management (public good, complex social-ecological network, uncertainty of economic, social and biological parameters, missing markets due to systemic and catastrophic nature of impacts and the existence of asymmetric information). At the start of my PhD, there was policy interest in cost and responsibility sharing, in particular Australia's Emergency Plant Pest Response Deed (EPPRD), a novel cost and responsibility sharing PPP between government and industry representative to manage pest and diseases. Naively motivated by the modelling challenges, my approach to answer the thesis objectives started with a simplistic view that PPPs could be captured with a single methodology. Over the course of the project, I learned that the complexity of modelling PPPs for pest management requires different methodologies.

The initial research objective was to identify suitable theoretical frameworks to model cost and responsibility sharing in PPPs. Methodologies including game theory, coalitions and cost sharing models from other fields (such as health sciences) were considered. In the end, I decided to use a principal-agent models as they are best suited to capture the interactions between private agents vs the government with asymmetric information. However, I found that this framework was too mathematically restrictive to capture collective behaviours. Thus, in Chapter 3, non-cooperative game theory was explored as a means of addressing this issue. Following two theoretical chapters, I was enthusiastic to take a different approach. The recent outbreak of a potato pest in northern Spain, provided the opportunity to develop an empirical paper using a choice experiment. Thus, having begun as a purely theoretical work, the focus of the thesis broadened to include more applied approaches to better capture the complexity of real world and the interdisciplinarity of the field.

Incorporating three different methodologies was one of the strongest aspects of the project. This highlighted the value of interdisciplinary work, captured the complexity of the issue, and helped me grow academically. The thesis therefore reflects my journey as a researcher, starting from a theoretical background to become an applied researcher. Additionally, the methodologies have rarely been utilised within the field of pest management. Therefore, this thesis's analysis and findings not only represent a contribution to plant health policy area but demonstrate how methodologies from other fields can be repurposed to inform the design of biosecurity PPPs.

However, this three-pronged approach also had it challenges and limitations. Three different methodologies covering different angles on an issue provides width, but at the expense of depth. For example, the chosen methods capture well the inter-relationship of both private and public behaviours well and how incentives need to be designed for uptake. This was achieved at the expense of using simplified biological/epidemiological modelling. Each chapter also demanded its own literature review and learning curve, making the journey a continuous uphill battle. Evaluating the thesis objectively, it could benefit from the inclusion of a case study to inform the design of incentives within PPPs. This would provide a more specific parameterisation challenge and would be a logical conclusion to the thesis

Regardless of the challenges, the research was an interesting and worthwhile experience, producing some personally surprising findings along the way. For example, Chapter 2 found that the most cost-effective biosecurity scheme only requires partial participation from private agents (Figure 3.5), contrary to the conventional view that such schemes require high or even full uptake to be effective. In Chapter 3, to the question "Do you think you should be compensated for those efforts", 14.79% of respondents claimed that they shouldn't receive compensation because it is the grower's responsibility to manage pest risks; a further 35.92% answered that they should only be partially compensated. Moreover, while crop insurance is voluntary in Spain, roughly half of the respondents claimed that crop insurance should be made mandatory, and over 75% believe that insurance is a better risk management mechanism than *ad hoc* compensation payments. Coming from an economic background, I found these findings conflicting with often taught mantras that private agents often prefer incentives to regulation.

5.5 Opportunities for future work

Some recommendations emerge from this thesis for future research, which may help to increase understanding on the design of PPPs for plant pest and disease management.

Exploration of inspections and contract enforcement

In this thesis I have focused on policy design that accounts for private agent motivations. However, the role of contract enforcement and inspections to ensure that the agreed effort levels are being conducted by all agents was ommitted. For example, in Chapter 2, I used complete contracts, an approach that has dominated the literature of asymmetric information. This type of agreed contract specifies all conditions of the contract under all contingencies, and is fully enforceable, i.e. it is completely state contingent, unlike the real world. Future work could develop an incomplete contract approach (such as Wu, 2014) to analyse the role of surveillance and commitment. On this topic, existing literature on arms control and disarmament contexts applies inspection games in the field of game theory, to model a situation where an inspector verifies that another agent, the inspectee, complies with the agreement reached previously (Dresher, 1962; Aumann & Maschler, 1966), which has also been applied more lately within an animal health setting (Gramig et al., 2009; Jin & McCarl, 2006). While in the past it was often argued that inspections and surveillance costs can be substantial and imperfect (Surkov, Oude Lansink & van der Werf, 2009; White & Hanley, 2016), new technology such as remote sensing is making such processes more cost effective and generating new sets of data. Finding ways of utilising and incorporating these new sources of information is an area in for future attention.

Modelling a policy network system

As the policy arena becomes more complex and interconnected, there is a need for future work to explore how to design a network of PPPs, where crucial information is shared, and biosecurity efforts are aligned towards an agreed biosecurity objective to monitor the broader system being managed. Coordinating such a network of PPPs (e.g. across multiple scales or trading sectors) to achieve a broader health quality goal is a major challenge. Of special importance will be the nature of the relations among the biosecurity actions carried out in different partnerships (for example if they are complementary or substitutes in the provision of the private and public goods). For example, in Chapter 3 I assumed that government- and agent-level biosecurity efforts are perfect substitutes, whereas often government efforts may be complementary to agents' actions (Kobayashi & Melkonyan, 2011). Bate et al. (2017) shows that even at the individual level, the type or relationship between own-management practices (prevention, and control) change depending on disease epidemiology. When the disease spread exceeds the ability to control it prevention and control are complements. Instead, when the ability to control the disease exceeds its rate of spread, prevention and control are substitutes. If the particular biosecurity management problem requires coordination and cooperation of multiple agents involved in different networks, the challenge is exacerbated since the network of schemes must work towards reinforcing biosecurity-weak industries (Epanchin-Niell & Wilen, 2014; Perrings, Burgiel, Lonsdale, Mooney, & Williamson, 2010; Cacho, Spring, Hester, & MacNally, 2010). As previous policies failed to implement efficient management practices for plant health due to a lack of cohesion and incoordination across jurisdictional areas (Stokes, Montgomery, Dick, Maggs, & McDonald, 2006), moving forwards researchers and policy makers must explore and develop consolidated policies that account for the system of policy networks where stakeholders operate.

Dynamics

It is important to note that in this thesis I overlooked the dynamics over time of both the disease and agent efforts and focused on what can be achieved in one-time step. In static models, as shown in the results of the previous chapters, the government provides direct incentives to agents through contracts and agreements. Decisions by both private agents and government, while being in a specific order (Figure 2.1), they are made in one time period. Because the agreement does not roll on to the next year, agents have no incentives to invest more in biosecurity efforts, even if it means that the risk of pests might decrease in the future (Finnoff, Shogren, Leung, & Lodge, 2007). This means that the agents were not modelled to choose their management efforts in a strategic way according to the dynamics nature of plant pest and disease risk. Similarly, it might be that the current biosecurity efforts not only affect present contingent payments but also the terms of future payments. Dynamic principal-agent or game theory models overcome those issues by focusing on how the interactions change over time, and this is an area in need of exploration (Lohr et al., 2017; Epanchin-Niell, 2017; Cobourn, Amacher & Haight, 2019).

5.6 Policy impact

Plant biosecurity has been highlighted as an important area for governance due to the substantial benefits for the economy, the environment, and human health. For example, the 25-year Environment Plan (DEFRA, 2018a), includes the objective to "make biosecurity central to all buying decisions". Moreover, the new Tree Health Resilience Strategy (DEFRA, 2018b) recognises the need for pest management activities across the biosecurity continuum (pre-border, border and inland), and the value of contingency planning and collective work between the private and public sectors. In this context, and in anticipation of the new Plant Health Biosecurity strategy to be published in 2020 (DEFRA, 2018b), understanding the drivers and behaviours underlying the decision-making process of industry and private agents and assessing their strategies and social interactions is critical to enhance national biosecurity. Lastly, the Food and Agricultural Organisation has named 2020 the International Year of Plant Health, as an opportunity to highlight the challenges around pest and disease management, as well as to raise awareness on how protecting plant health can support environmental, social and economic development. A series of events are taking place across the globe to bring together scientist, researchers and policy makers to tackle plant pest and disease challenges.

Motivated by previous challenges and current policy interest, this thesis explored modelling frameworks that can aid PPP policy design by incorporating different behaviours and interactions among the public and private sector. The research illustrates the value of contingent PPPs as a mechanism to share the costs, risks and responsibilities from pest and diseases. It also identifies scheme characteristics that would deliver cost effective approaches while achieving high industry support. For example, agreeing on the structure of payments prior to outbreaks and having payments that not only depend on one's own performance, but everyone else's would decrease risk among scheme signatories (Chapter 2). Moreover, payments should only cover partial damages, thus typical government compensation levels should be reduced and resources diverted towards other activities, such as prevention activities (Chapter 3). However, it is important to note that no PPP fits all and it is crucial to ensure that different pest management policies are aligned with each other. Should governments decide to subsidise national crop or horticultural insurance (to achieve some the benefits outlined in Chapter 4), or support the establishment of an industry scheme, PPPs should be aligned with alternative incentives such as *ad hoc* payments and regulatory requirement to provide a coordinated policy network.

Regardless of its limitations, this thesis has shown some of the potential benefits of PPPs in delivering a cost-effective approach to biosecurity, and provides a framework to stimulate explorations about the role of government policies in supporting private agent contributions to plant health. Despite the potential benefits of pre-emptive PPPs, there is still limited understanding on how to motivate private participation in biosecurity efforts under a cost and responsibility sharing contingent agreement. Further understanding about the interactions between the public and private sectors is of relevance in order to develop effective and efficient plant health future policies. This would help better understand and anticipate the likelihood of success of biosecurity policy based on partnerships and public-private collaboration (e.g. the success of the volunteer network Observatree or the Action Oak initiative; the industry led Plant Health Assurance Scheme (PHAS) currently in development). This work not only contributed to the theoretical literature of instruments available to deal with pests but more importantly, I hope it provides support to policy makers on a novel management practice.

5.7 References

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Appendix 1 – Solving the principal-agent model

Online Appendix

SOLVING THE GOVERNMENT'S PROBLEM

First we can solve the agent's maximisation problem:

$$\mathbb{E}\left[-e^{-\eta_1[w_1+\delta_1\, q_1\, -\phi_1(a_1)]}\right] = \mathbb{E}\left[-e^{-\eta_1[z_1+v_1q_1+h_1q_2+\delta_1\, q_1\, -\phi_1(a_1)]}\right]$$
$$= \mathbb{E}\left[-e^{-\eta_1[z_1+v_1(a_1+\xi_1+\alpha\xi_2)+h_1(a_2+\xi_2+\alpha\xi_1)+\delta_1\,(a_1+\xi_1+\alpha\xi_2)\, -\phi_1(a_1)]}\right]$$

If we rename
$[z_1 + v_1(a_1 + \xi_1 + \alpha\xi_2) + h_1(a_2 + \xi_2 + \alpha\xi_1) + \delta_1\,(a_1 + \xi_1 + \alpha\xi_2)\; - \phi_1(a_1)] = x$, then the above expression becomes $\mathbb{E}\left[-e^{-\eta_1(x)}\right]$

By the properties of the lognormal distribution:
$\mathbb{E}\left[-e^{-\eta_1(x)}\right] = -e^{\mathbb{E}[-\eta_1 x]+\frac{1}{2}Var[-\eta_1 x]} =$
$-e^{-\eta_1\left[z_1\, +\, v_1a_1+\, h_1a_2\, +\, \delta_1\, a_1-\, \frac{1}{2}ca_1^2\right]+\frac{1}{2}\eta_1^2 Var\,[v_1\xi_1+v_1\alpha\xi_2+h_1\xi_2+h_1\alpha\xi_1+\delta\xi_1+\delta\alpha\xi_2]} =$
$-e^{-\eta_1\left[z_1\, +\, v_1a_1+\, h_1a_2\, +\, \delta_1\, a_1-\, \frac{1}{2}ca_1^2\right]+\frac{1}{2}\eta_1^2\sigma^2\,[(v_1+h_1\alpha+\delta)^2+(h_1+v_1\alpha+\delta\alpha)^2]}$

Due to the properties of the exponential function, solving the above problem is equivalent to solving:
$\max_{\{a_1\}}\{\, z_1 + v_1a_1 + h_1a_2 + \delta a_1 - \frac{1}{2}ca_1^2 - \frac{1}{2}\eta_1\sigma^2[(v_1 + h_1\alpha + \delta)^2 + (h_1 + v_1\alpha + \delta\alpha)^2]\}$.

We can now take the first order conditions, and solve for the producer's chosen level of biosecurity efforts, given a set of payments:

F.O.C:

$$v_1 - ca_1 + \delta = 0$$
$$a_1 = \frac{v_1 + \delta}{c}$$

and by symmetry

$$a_2 = \frac{v_2 + \delta}{c}.$$

Once we have the optimal solution for the biosecurity level from the producer we can substitute it into the participation constraint:

$$z_1 + v_1\left(\frac{v_1+\delta}{c}\right) + h_1\left(\frac{v_2+\delta}{c}\right) + \delta\left(\frac{v_1+\delta}{c}\right) - \frac{1}{2}c\left(\frac{v_1+\delta}{c}\right)^2$$
$$-\frac{1}{2}\eta\sigma^2[(v_1+h_1\alpha+\delta)^2 + (h_1+v_1\alpha+\delta\alpha)^2] = u(\overline{w}).$$

Thus, we can rewrite the public sector's objective function as:

$$\max_{\{a_1,z_1,v_1,h_1\}} \mathbb{E}\,[q_1 - w_1]$$
$$= \max_{\{a_1,z_1,v_1,h_1\}} \mathbb{E}(a_1+\xi_1+\alpha\xi_2-(z_1+v_1(a_1+\xi_1+\alpha\xi_2)+h_1(a_2+\xi_2$$
$$+\alpha\xi_1)))$$
$$= \max_{\{z_1,v_1,h_1\}} \mathbb{E}\left(\frac{v_1+\delta}{c}+\xi_1+\alpha\xi_2-(z_1+v_1(\frac{v_1+\delta}{c}+\xi_1+\alpha\xi_2)+h_1(\frac{v_2+\delta}{c}\right.$$
$$\left.+\xi_2+\alpha\xi_1))\right)$$

subject to the incentive compatibility constraints.

After taking expectations:

$$\max_{\{z_1,v_1,h_1\}}\left(\frac{v_1+\delta}{c}-(z_1+v_1\left(\frac{v_1+\delta}{c}\right)+h_1\left(\frac{v_2+\delta}{c}\right))\right)$$

subject to

$$z_1 + v_1\left(\frac{v_1+\delta}{c}\right) + h_1\left(\frac{v_2+\delta}{c}\right) + \delta\left(\frac{v_1+\delta}{c}\right) - \frac{1}{2}c\left(\frac{v_1+\delta}{c}\right)^2$$
$$-\frac{1}{2}\eta_1\sigma^2[(v_1+h_1\alpha+\delta)^2 + (u_1+h_1\alpha+\delta\alpha)^2] = u(\overline{w}).$$

Because the constraint binds, it is possible to rewrite the problem as an unconstrained optimisation problem:

$$\max_{\{v_1,h_1\}}\left(\frac{v_1+\delta}{c}+v_1\left(\frac{v_1+\delta}{c}\right)+h_1\left(\frac{v_2+\delta}{c}\right)+\delta\left(\frac{v_1+\delta}{c}\right)-\frac{1}{2}c\left(\frac{v_1+\delta}{c}\right)^2\right.$$
$$\left.-\frac{1}{2}\eta_1\sigma^2[(v_1+h_1\alpha+\delta)^2+(h_1+v_1\alpha+\delta\alpha)^2]-v_1\left(\frac{v_1+\delta}{c}\right)-h_1\left(\frac{v_2+\delta}{c}\right)\right)$$

After some algebra:

$$\max_{\{v_1,h_1\}}\left(\frac{v_1+\delta}{c}(1+\delta)-\frac{1}{2}c\left(\frac{v_1+\delta}{c}\right)^2-\frac{1}{2}\eta_1\sigma^2[(v_1+h_1\alpha+\delta)^2+(h_1+v_1\alpha+\delta\alpha)^2]\right)$$

We can now take taking first order conditions with respect to h_1 and v_1 :

$$\frac{\partial}{\partial h_1} = \frac{1}{2}\eta_1\, \sigma^2[2(v_1 + h_1\alpha + \delta)\alpha + 2(h_1 + v_1\alpha + \delta\alpha)] = 0$$

Solving for h_1:

$$h_1 = -\left(\frac{2\alpha\,(\delta + v_1\,)}{\alpha^2 + 1}\right)$$

Taking FOC:

$$\frac{\partial}{\partial h_1} = \frac{\delta + 1}{c} - \frac{2v_1 + 2\delta}{2\,c} - \frac{1}{2}\eta_1\sigma^2[2(v_1 + h_1\alpha + \delta) + 2\,\alpha\,(h_1 + v_1\alpha + \delta\alpha)] = 0$$

Solving for v_1 and h_1 :

$$v_1 = \frac{(1 + \alpha^2)(\delta + 1)}{1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2} - \delta$$

$$h_1 = -\left(\frac{2\alpha(\delta + 1\,)}{1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2}\right)$$

$$a_1 = \frac{(1 + \alpha^2)(\delta + 1)}{c(1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2)}$$

$$z_1 = \left(\frac{1}{2}\right)\frac{(1 + \alpha^2)(\delta + 1)^2(\alpha^4 c\eta\sigma^2 + (-2c\eta\sigma^2 - 1)\alpha^2 + 4\alpha + c\eta\sigma^2 - 1)}{c(1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2)^2}$$

EXPECTED VALUES

The expected quality of the crops:

$$\mathbb{E}[q_i] = \mathbb{E}\left[a_i + \xi_i + \alpha\xi_j\right] = \frac{(1+\alpha^2)(\delta+1)}{c(1+\alpha^2+c\eta_i\sigma^2(1-\alpha^2)^2)}$$

Expected total value of payments:

$$\mathbb{E}[w_i] = \mathbb{E}\left[z_i + v_i q_i + h_i q_j\right] = \mathrm{z_i} + v_i\left(\frac{v_i + \delta}{c}\right) + h_i\left(\frac{v_j + \delta}{c}\right)$$

$$= -\delta\left(\frac{v_1 + \delta}{c}\right) + \frac{1}{2}c\left(\frac{v_1 + \delta}{c}\right)^2 + \frac{1}{2}\eta_i\sigma^2[(v_1 + h_1\alpha + \delta)^2 + (h_1 + v_1\alpha + \delta\alpha)^2]$$

$$= \frac{-(1 + \alpha^2)(\delta^2 - 1)}{c(1 + \alpha^2 + c\eta_i\sigma^2(1 - \alpha^2)^2)}$$

Expected utility of the government:

$$\mathbb{E}(q_1 - w_1 + q_2 - w_2) = = \frac{(1 + \alpha^2)(\delta + 1)^2}{c(1 + \alpha^2 + c\eta_i\sigma^2(1 - \alpha^2)^2)}$$

Expected utility of the producers:

$$\mathbb{E}\left[-e^{-\eta_i[w_i+\delta_i\, q_i\, -\phi_i(a_i)]}\right]$$

$$= \; z_i + v_i a_i + h_i a_j + \delta a_i - \frac{1}{2} c a_i^2$$

$$-\frac{1}{2}\eta_i \sigma^2[(v_i + h_i\alpha + \delta)^2 + (h_i + v_i\alpha + \delta\alpha)^2] = 0$$

SPECIAL CASE ($\boldsymbol{\delta = 0}$)

We can look at the specific scenario when the producer income is only dependent on the payments and cost of biosecurity levels ($\delta = 0$).

$$\max_{\{a_1, z_1, v_1, h_1\}} \mathbb{E}(q_1 - w_1)$$

subject to

$$\mathbb{E}[-e^{-\eta_1[w_1\, -\phi_1(a_1)]}] \geq u(\overline{w})$$

and

$$a_1 \; \in arg\, max_{\{a\}}\, \mathbb{E}[-e^{-\eta_1[w_1\, -\phi_1(a_1)]}]$$

Under this scenario, the optimal biosecurity effort is

$$a_i = \frac{v_i}{c}$$

The problem of the government becomes

$$\max_{\{\, z_1, v_1, h_1\}} \left(\frac{v_1}{c} - (z_1 + v_1\left(\frac{v_1}{c}\right) + h_1\left(\frac{v_2}{c}\right))\right)$$

subject to

$$z_1 + v_1\left(\frac{v_1}{c}\right) + h_1\left(\frac{v_2}{c}\right) - \frac{1}{2}c\left(\frac{v_1}{c}\right)^2 - \frac{1}{2}\eta_1\sigma^2[(v_1 + h_1\alpha)^2 + (h_1 + v_1\alpha)^2] = \; u(\overline{w})$$

The unconstrained problem becomes:

$$\max_{\{v_1, h_1\}} \left(\frac{v_1}{c} - \frac{1}{2}c\left(\frac{v_1}{c}\right)^2 - \frac{1}{2}\eta_1\sigma^2[(v_1 + h_1\alpha)^2 + (h_1 + v_1\alpha)^2]\right)$$

Taking F.O.C for v_1 and h_1 and solving for the variables:

$$v_1 = \; \frac{(1 + \alpha^2)}{1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2}$$

$$h_1 = \; -\left(\frac{2\alpha}{1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2}\right)$$

$$a_1 = \frac{(1 + \alpha^2)}{c(1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2)}$$

$$z_1 = \left(\frac{1}{2}\right)\frac{(1 + \alpha^2)(\alpha^4 c\eta\sigma^2 + (-2c\eta\sigma^2 - 1)\alpha^2 + 4\alpha + c\eta\sigma^2 - 1)}{c(1 + \alpha^2 + c\eta_1\sigma^2(1 - \alpha^2)^2)^2}$$

The expected quality of the crops:

$$\mathbb{E}[q_i] = \mathbb{E}\left[a_i + \xi_i + \alpha\xi_j\right] = \frac{(1+\alpha^2)}{c(1+\alpha^2+c\eta_1\sigma^2(1-\alpha^2)^2)}$$

Expected total value of payments:

$$\mathbb{E}[w_i] = \mathbb{E}\left[z_i + v_i q_i + h_i q_j\right] = \mathrm{z_i} + v_i\left(\frac{v_i}{c}\right) + h_i\left(\frac{v_j}{c}\right) = \frac{(1+\alpha^2)}{2c(1+\alpha^2+c\eta_i\sigma^2(1-\alpha^2)^2)}$$

Expected utility of the government:

$$\mathbb{E}(q_1 - w_1 + q_2 - w_2) = \frac{(1+\alpha^2)}{c(1+\alpha^2+c\eta_i\sigma^2(1-\alpha^2)^2)}$$

Expected utility of the producers:

$$\mathbb{E}\left[-e^{-\eta_i[w_i - \phi_i(a_i)]}\right] = z_i + v_i a_i + h_i a_j - \frac{1}{2}ca_i^2 - \frac{1}{2}\eta_i\sigma^2[(v_i + h_i\alpha)^2 + (h_i + v_i\alpha)^2] = 0$$

DISCUSSION: IMPORTANCE OF $\boldsymbol{\delta}$

Relative change in biosecurity efforts: $\frac{a_i - a_i^*}{a_i^*} = \delta$

Relative change in own marginal payments: $\frac{v_i - {v_i}^*}{{v_i}^*} = -\frac{\sigma^2\eta\delta c\left(\alpha^2-1\right)^2}{\alpha^2+1}$

Relative change in neighbor marginal payments: $\frac{h_i - h_i^*}{h_i^*} = \delta$

Relative change in expected fixed payments: $\frac{\mathbb{E}[z_i] - \mathbb{E}[z_i^*]}{\mathbb{E}[z_i^*]} = \delta^2 + 2\delta$

Relative change in expected total payments received by the producers: $\frac{\mathbb{E}[w_i] - \mathbb{E}[w_i^*]}{\mathbb{E}[w_i^*]} = -\delta^2$

Relative change in expected crop quality levels: $\frac{\mathbb{E}[q_i] - \mathbb{E}[q_i^*]}{\mathbb{E}[q_i^*]} = \delta$

Relative change of Government Utility: $\frac{\mathbb{E}[\boldsymbol{U}] - \mathbb{E}[\boldsymbol{U}^*]}{\mathbb{E}[\boldsymbol{U}^*]} = \delta^2 + 2\delta$

Appendix 2 – Farmer survey

(TRANSLATED FROM SPANISH)

Section 1: Demographic questions

1. Gender: Female ☐ Male ☐
2. Age: ___________
3. Which is the higher level of education you have completed or you are in process of completing?
   a) Less than primary school ☐
   b) Primary school ☐
   c) Secondary ☐
   d) University ☐

Section 2: Farm and land related questions

4. In what municipality is the farm located? _____________________
5. What is the approximate size of your farm (total number of hectares): ________________
6. Are you a vegetable producer?
   Yes ☐ No ☐ (If No, leave survey)
7. What area (hectares) do you grow with vegetables? ___________________
8. Please, mark which vegetables you grow?

   Chard ☐
   Artichokes ☐
   Eggplant ☐
   Zucchini ☐
   Onion ☐
   Coles ☐
   Spinach ☐
   Pea ☐
   Beans ☐
   Blackberry ☐
   Cucumber ☐
   Leek ☐
   Garlic ☐
   Celery ☐
   Sweet potato ☐
   Pumpkin ☐
   Mushrooms ☐
   Asparagus ☐
   Strawberry ☐
   Bean ☐
   Lettuce ☐
   Potato ☐
   Pepper ☐
   Beet ☐
   Others:_____________
9. How many hectares to you grow with potatoes? __________________
10. Approximately what percentage of family income is derived from vegetable production

    0%-5% ☐
    5-25% ☐
    25-45% ☐
    45%-65% ☐
    65-100% ☐
    Don't know ☐
    Prefer not to answer ☐

11. Do you belong to an agrarian cooperative or are you a member of a crop production group?

Yes ☐ No ☐

Section 3: Insurance questions

12. Have you ever purchased agricultural insurance?

Yes ☐ No ☐

13. How would you rank your knowledge of agrarian insurances available to you?

Very High ☐ High ☐ Medium ☐ Low ☐ Very Low ☐

Below are different features that describe agricultural insurance

PRODUCTION REQUIREMENTS Insurance requires that the following production measures be taken for risk management.
STANDARD MEASURES The insurance program requires production practices as currently specified in the Official State Journal
ADDITIONAL REQUIREMENTS The insurance program requires additional production practices for risk reduction. In particular, it requires compliance with the measures established in the technical standards of integrated production or specified requirements of plant health groups. This implies that production will be subject to regular controls and must keep records of all prevention and control measures taken. In addition, the use of certified seeds and a register for product traceability is mandatory. The producer will also be required to take a training course every three years, in which subjects of plant health, biological threats, and production methods of integrated control will be taught.

DEDUCTIBLE The deductible represents the expected production cost that the producer assumes and that in no case will the insurance cover. The deductible can be of the following percentages		
10 %	**20 %**	**30 %**

COVERAGE The insurance covers damages caused by specific risks and can have the following coverage.
A. Basic coverage The risks covered are climatic adversities (hail, frost, persistent rain, flooding, high wind and fire) and damages cause by wild animals
B. Medium coverage This option includes all risks covered under basic coverage and damages caused to the production and quality of the crops due to plagues, diseases, virology, and pests that are recurrent.
C. High coverage This option includes all risks covered under medium coverage and compensation for damages caused by quarantine pests, alien species, and emerging diseases and pathologies that require periods of production bans or destruction and removal of the plantation and product, as established in national eradication and containment plans.

GOVERNMENT CO-PAYMENT (DURING CATASTROPHIC EVENTS) The government can promote the use of combined agricultural insurance against extreme events. Therefore, the government can commit to cover the insurance deductible in extreme events (for example in the case of pests or emerging diseases of great impact and that require special control measures, or natural catastrophes) and in a certain maximum time.		
Co-payment paid within 2 months	Co-payment paid within 6 months	No government co-payment

Part 4: Choice Experiment

Next, we show you exercises of choice with different vegetable insurance options for your exploitation. Please, in each case, mark the insurance you would take. Remember that you always have the option of not choosing the insurance presented. Note that, in all cases, the amount in case of compensation would be calculated using the unit prices established in the BOE and in the same way as is currently done in existing combined agricultural insurance.

CARD 1:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	Basic	Medium	High	☐
PRODUCTION MEASURES	Additional	Standard	Additional	
DEDUCTIBLE	30%	10%	20%	
CO-PAYMENT	Payment in 2 months	Payment in 6 months	Payment in 2 months	
PRICE	14 €/ha	42 €/ha	56 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

CARD 2:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	High	Basic	Medium	☐
PRODUCTION MEASURES	Additional	Standard	Additional	
DEDUCTIBLE	20%	20%	10%	
CO-PAYMENT	Payment in 2 months	Payment in 6 months	No payment	
PRICE	84 €/ha	56€/ha	70 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

CARD 3:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	Medium	High	Basic	☐
PRODUCTION MEASURES	Standard	Standard	Additional	
DEDUCTIBLE	10%	30%	30%	
CO-PAYMENT	Payment in 2 months	Payment in 2 months	Payment in 2 months	
PRICE	56 €/ha	70 €/ha	14 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

CARD 4:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	Basic	Medium	High	☐
PRODUCTION MEASURES	Standard	Additional	Additional	
DEDUCTIBLE	20%	30%	30%	
CO-PAYMENT	No payment	Payment in 2 months	Payment in 6 months	
PRICE	42 €/ha	56 €/ha	70 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

CARD 5:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	High	Basic	Medium	☐
PRODUCTION MEASURES	Standard	Standard	Standard	
DEDUCTIBLE	20%	20%	30%	
CO-PAYMENT	Payment in 6 months	Payment in 6 months	Payment in 2 months	
PRICE	70 €/ha	14 €/ha	56 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

CARD 6:

CHARACTERISTICS OF THE INSURANCE PROGRAMME	INSURANCE A	INSURANCE B	INSURANCE C	NONE
COVERAGE	Medium	High	Basic	☐
PRODUCTION MEASURES	Standard	Standard	Additional	
DEDUCTIBLE	10%	10%	20%	
CO-PAYMENT	Payment in 6 months	No payment	Payment in 6 months	
PRICE	42 €/ha	56 €/ha	28 €/ha	
Your preferred option	☐	☐	☐	
Your least preferred option	☐	☐	☐	

Part 5: Debriefing questions

14. When choosing, have you taken into account all the characteristics of the insurance?
    Yes ☐ No ☐

15. If No Which of the following characteristics you didn’t take into account?
    a) Coverage ☐
    b) Production measures ☐
    c) Deductible ☐
    d) Co-payment ☐
    e) Price ☐
16. How easy was choosing an option?
    Very difficult ☐ Difficult ☐ Neither difficult nor easy ☐

    Easy ☐ Very easy ☐

17. If you chose neither insurance programme (option C) in all of the choice sets above, could you please tell us why?
    a) I do not think that crop insurance is necessary, there is no risk ☐

b) I do not have the financial capacity to take up insurance ☐
c) I prefer to use the money in other risk management strategies ☐
d) The government should pay ☐
e) I am not interested in insurance, I can manage the risks without it ☐
f) I don't have enough information about the insurance policy ☐
g) Other (please specify) _______ ☐

Part 6: Risk related questions

18. Please, can you tell us to what extent do the following risks affect your crop production

Hazards	Very high extent	High extent	Moderate	Low extent	Very low extent
Climatic					
Pest, diseases, and invasive species					
Variation in yield					
Fluctuation of crop prices					

19. To what extent do you conduct efforts to avoid, prevent, or control the introduction or spread of pests, plant diseases, or invasive species (such as felling, destruction of infected crops, use of pesticides, etc.)?

Very high extent ☐ High extent ☐ Moderate ☐

Low extent ☐ Very low extent ☐

20. If not very low extent. Do you think you should be compensated for those efforts?

Yes, totally ☐ Yes, partially ☐ No ☐

21. Have you experienced crop loss larger than 30% in production quality of quantity due to pests, invasive species, or diseases in the last 5 years?

Yes ☐ No ☐

22. If yes, have you been compensated for the financial losses suffered?

a) Yes, totally ☐
b) Yes, partially ☐
c) No ☐

23. Do you think you will suffer crop loss larger than 30% in production quality of quantity due to pests, invasive species, or diseases in the next 5 year?
Yes ☐ No ☐

24. Compared to the average person, I would say I take more risks:

Strongly Disagree ☐ Disagree ☐ Neither Agree or Disagree ☐

Agree ☐ Strongly Agree ☐

Part 4: Insurance preference questions

25. Are you satisfied with the current crop insurance scheme?

Strongly Satisfied ☐ Satisfied ☐ Neither Satisfied nor Dissatisfied ☐
Dissatisfied ☐ Strongly Dissatisfied ☐

26. If dissatisfied or strongly dissatisfied. Please mark the reasons for dissatisfaction.

a) High premiums ☐
b) Delay in compensation payment ☐
c) Main risks are not covered ☐
d) Payments are very low ☐

27. What are your suggestions for improving agricultural insurance?

a) Cover more crops ☐
b) Cover more risks ☐
c) Different method to calculate indemnities ☐
d) Reduce premium ☐
e) Quick settlement of claims ☐
f) Increase government insurance subsidies ☐
g) Provide more information, conduct crop insurance workshops ☐
h) Others (specify): ___________________

28. Do you think agriculture insurance should be made compulsory?

Yes ☐ No ☐

29. Do you think crop insurance is a better risk management strategy than waiting to receive disaster relief after the occurrence of the disaster?

Yes ☐ No ☐

30. Would you like to receive an update with the results of the project?

Yes ☐ No ☐

If you have answered “yes”, please provide an email where we can send you a summary of the results: ____

Glossary

ASC – Alternative specific constant

BAM Act – Biosecurity and Agriculture Management Act

BOE – Official State Journal

CAP – Common Agricultural Policy

CE – Choice experiment

DAFWA – Department of Agriculture and Food of Western Australia

DEFRA – Department of Environment, Food and Rural Affairs

DPIRD - Department of Primary Industries and Regional Development

DPR – Declared Pest Rate

ENESA – State Entity for Agricultural Insurance

EPPRD – Emergency Plant Pest Response Deeds

HTA – Horticultural Trades Association

MAPAMA - Ministry of Environment and Rural and Marine Affairs

mWTP – Marginal willingness to pay

NARF – Natural Area Reserve Fund

OECD - Organisation for Economic Co-operation and Development

PCIC – Philippine Crop Insurance Corporation

PHAS – Plant Health Assurance Scheme

PPP – Public-private partnership

RBG – Recognised Biosecurity Group

RPL – Random parameters logit

Sd mWTP – Standard deviation of the marginal willingness to pay

US MPCI – US Multiple Peril Crop Insurance

WTP - Willingness to pay