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

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Abstract: Private efforts to prevent and control biological pests and infectious diseases can be a public good, and so incentivizing 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.

Key words: risk sharing, public-private partnerships, contract theory, plant and tree health, compensation payments

JEL Classifications: Q18, Q10, Q58

1. INTRODUCTION

The number of plant and animal disease and pest outbreaks is increasing rapidly as a consequence of globalization of trade and travel. Developing efficient management plans for prevention and control is of key importance to avoid economic, environmental and human

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health impacts (e.g. Bebber et al., 2014; Donovan 2013; Simberloff, 2012; Dalmazzone and Giaccaria, 2014). 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 Horan and Lupi, 2010; Keller et al., 2011; Epanchin-Niell, 2017; Lodge et al. 2016).

In economic terminology, policies to manage pests have public good characteristics (Perrings et al., 2002; Perrings 2005). 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 and 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, land owners, 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, 2008; Mills et al., 2011; Humair et al., 2014; Reed and 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 (Mumford, 2011; Cook et al. 2010).

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 (Ramsay, Philip and Riethnuller, 1999; Perrings et al., 2002; Epanchin-Niell, 2017). 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, 2011). 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 (OECD, 2011; Bremmer and Slobbe 2011).

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 (Potatopol 2010)), 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[2] (Plant Health Australia, 2014; Animal Health Australia, 2016).

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 (Mumford, 2011; Cook et al., 2010; Krauss and Duffy, 2010; Waage et al., 2005; Mumford, 2002). PPPs have the potential additional benefit of being a pre-agreed policy before an outbreak occurs, thereby reducing the response time and minimizing the size and impact of the incursion (Leung et al., 2004; Heikkila and Peltola, 2004; Kaiser and Burnett, 2010; Sims and 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 and 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

[2] 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 (Mumford 2011; Anderson 2005; Cook et al., 2010). The scheme describes the rules on splitting the costs between the public and the private sector depending on the potential damages of the pests.

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 and Mumford, 2008; Wilkinson et al., 2001). Due to these challenges, compensation for breaches in plant health is much less common (Mumford, 2001). While this study is motivated by a desire to control plant pests, the model and its implications may also generalize 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 land owners, conducting biosecurity efforts while receiving compensation payments for their actions. Given the impure public good character of agents' biosecurity actions (Reeling and 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 damages caused by the pest, such as the effect of weather on pathogen spread and life-cycle (Whittaker et al., 2001; Guernier et al., 2004) 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 3. The analytical results are complemented with numerical simulations in Section 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. 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 damages, 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 on property values, affect recreational opportunities, and reduce human health and well-being (e.g. Pennisi 2010; Kovacs et al., 2011; Jones 2016; Kondo et al., 2017).

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 effectives of efforts to achieve the outcome (White and Hanley 2016; Engel, 2016; Börner et al., 2017). 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 and Dewatripont, 2005; Hanley et al., 2012; White and 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 Recognized Biosecurity

Groups in Western Australia, have compensation programmes set up in a different format: there 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[3]; Recognised Biosecurity Groups, 2017).

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.

2.1. THE AGENTS

We consider two independent, identical, and representative agents, labelled by subscripts 1 and 2, each in charge of producing healthy plants by conducting biosecurity efforts, 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. 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 units:

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

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

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

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[4]. 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[5] 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 receiving payment w_i for biosecurity efforts a_i to be written as follows:

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

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 related to the surveillance and control levels applied:

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

[4] 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 reviewer for suggesting this alternative specification.

[5] 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.

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

2.2. 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:

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

2.3. THE PAYMENTS

Following contract theory, models of performance based payments typically consist of two parts: a fixed payment and a variable incentive payment (Bolton and 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 and Dewatripont, 2005). The government's linear incentive scheme is:

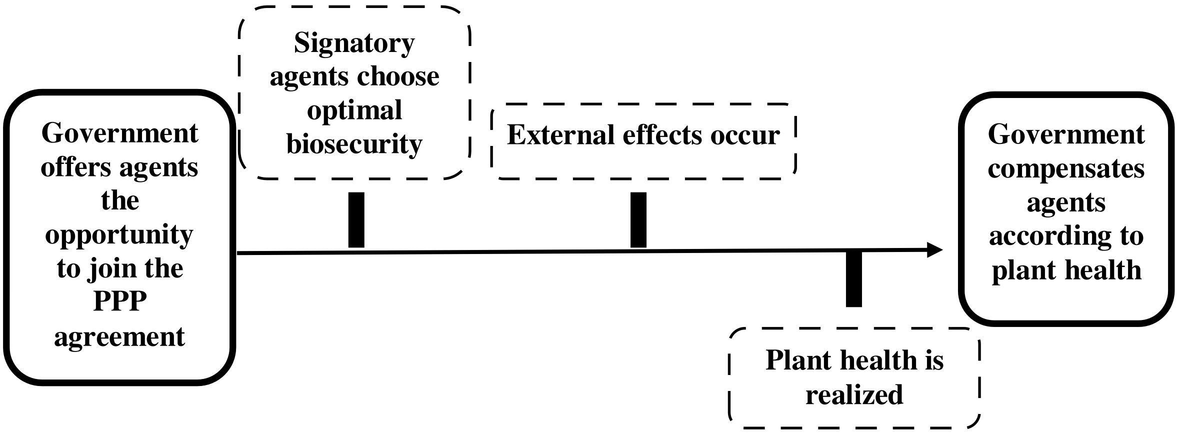
$$w_i = z_i + v_i q_i + h_i q_j \qquad (5)$$

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. 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 maximize their own expected utility. Uncontrollable effects then occur that affect plant health and the occurrence of pest damages. Plant health quality is realized by both agents and the government, and agents receive the payment based on the quality of the plants on their land.

Figure 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 maximizes its expected utility in relation to agent 1 by solving:

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

subject to:

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

and

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

That is, the government maximizes expected utility subject to the participation (eq. 7) and incentive compatibility constraints (eq. 8) of the representative agent. $u(\overline{w})$ represents the utility of wealth associated with the option of not participating in the scheme. Without loss of generality, we set $u(\overline{w}) = 0$.

The problem can be transformed into an unconstrained optimization problem[6]. The first step is to solve the agent's maximization 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 maximization problem becomes:

[6] In the on-line Appendix we include the detailed step-by-step process of solving the problem of the government.

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

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

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

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.

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

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

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 minimize the risk (third and fourth term of equation 11) and then v_1 is set optimally to trade off risk sharing and incentives:

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

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

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 and Dewatripont, 2005). This can be seen in the optimal marginal payments (eq. 12 and eq.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 (eq. 14); that is z_1 becomes the residual of the incentive participation constraint (eq. 7). The fixed payment is then set so that the private benefits derived by the agent from joining the contract 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:

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

3. IMPLICATIONS OF THE OPTIMAL PPP SOLUTION

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

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

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

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

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:

$$\mathbb{E}(q_1 - w_1 + q_2 - w_2) = \frac{(1+\alpha^2)(\delta_i + 1)^2}{c_i(1+\alpha^2 + c_i\eta_i\sigma^2(1-\alpha^2)^2)} \tag{17}$$

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

$$\mathbb{E}\left[-e^{-\eta_i[w_i+\delta_i q_i - \phi_i(a_i)]}\right]$$
$$= z_i + v_i a_i + h_i a_j + \delta_i a_i - \frac{1}{2}c_i a_i^2$$
$$-\frac{1}{2}\eta_i\sigma^2[(v_i + h_i\alpha + \delta_i)^2 + (h_i + v_i\alpha + \delta_i\alpha)^2] = 0 \tag{18}$$

3.1. 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 (eq. 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 summarized in Table 1.

Table 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	$\frac{\partial \mathbb{E}[q_i]}{\partial c_i} < 0$	$\frac{\partial \mathbb{E}[q_i]}{\partial \eta_i} < 0$	$\frac{\partial \mathbb{E}[q_i]}{\partial \sigma^2} < 0$
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.

3.2. 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 land-owner may overlook the benefits of preemptive 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 summarized in Table 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: 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	$\boldsymbol{v_i}$	$-\frac{\sigma^2\eta\delta c(\alpha^2-1)}{\alpha^2+1}$	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.

4. NUMERICAL ILLUSTRATION

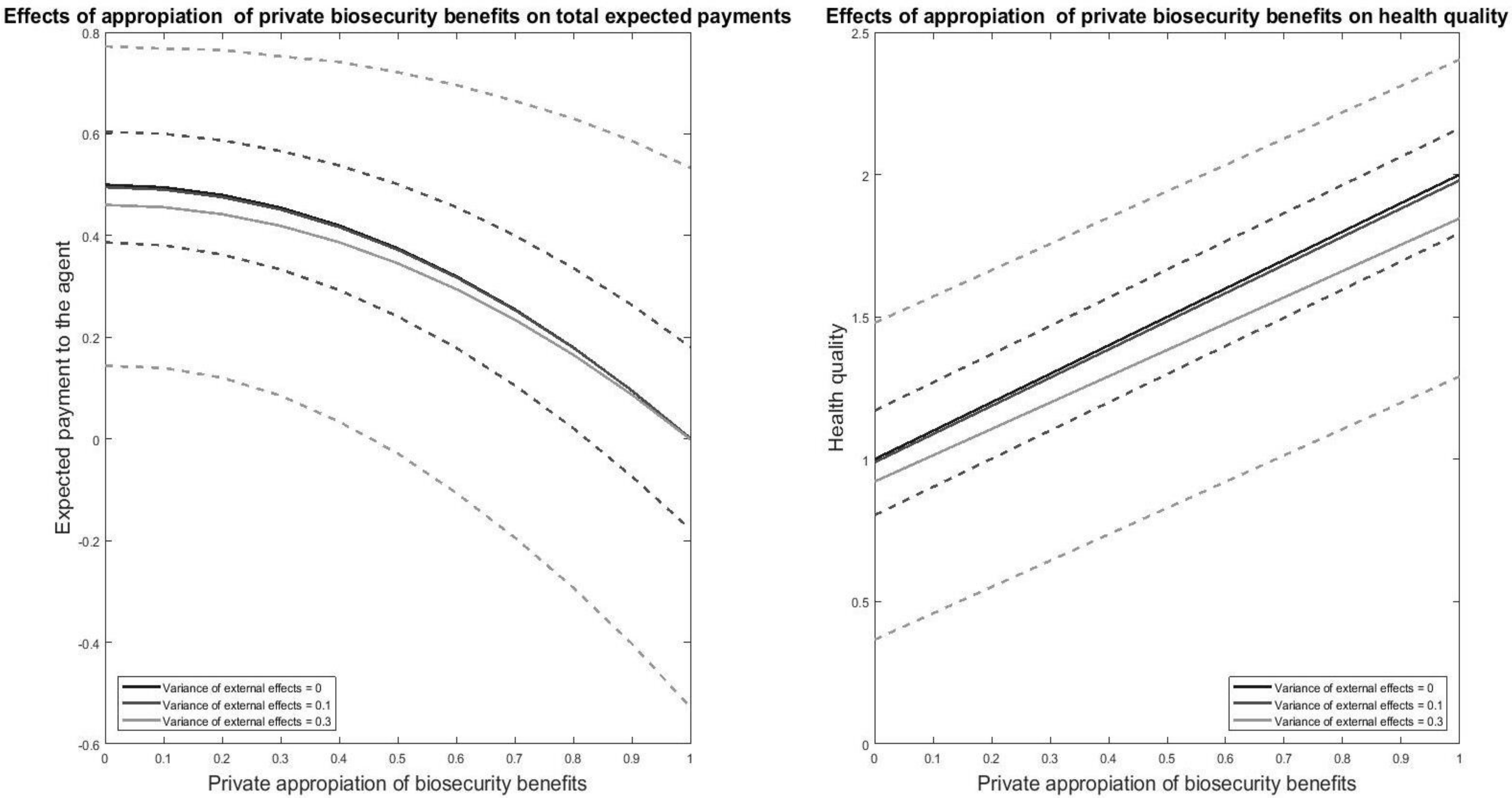
A numerical simulation illustrates the effects of different levels of appropriation of private biosecurity benefits on total payments received by the agent and final plant health quality achieved with the PPP scheme. Representative parameter values (Table 3) are given to the marginal cost of biosecurity 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 1. This exercise was run for three different levels of variance of external effects.

Table 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 left plot in Figure 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 realizations. 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 right plot in Figure 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, the plant health increases proportionally.

Figure 1: Expected payments and plant health for different degrees of private appropiation of biosecurity benefits by agents, and levels of variance of external shocks (Simulation mean and 5% and 95% quantiles reported).



5. 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 stylized model that captures the most important generalizable 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 and Knowler, 2006; or Fraser, 2016), we instead focus on the social desirability of the compensation payment.

We show that, in principle, the risk minimization 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 of 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 et al., 2008; Hanley et al., 2012; Zabel and 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 which explore this issue in detail, for example Gramig et al., (2009) and Jin and McCarl (2006). Despite evidence of inspection costs being substantial (for example Surkov et al., 2009 and 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 and Slobbe, 2011) deserves consideration. Future research could explore further the potential for minimizing 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, 2011). 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.

6. 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 conceptualizing 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 (Defra, 2014; UK Plant Health Business Plan (2006–2008); 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 minimizing 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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PUBLIC-PRIVATE PARTNERSHIPS FOR BIOSECURITY: AN OPPORTUNITY FOR RISK SHARING

Rosa Mato Amboage, Jon Pitchford and Julia Touza

ON-LINE SUPPLEMENTARY INFORMATION

SOLVING THE GOVERNMENT'S PROBLEM

First we can solve the agent's maximization 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:

$$\max_{\{a_1, z_1, v_1, h_1\}} \mathbb{E}\,[q_1 - w_1]$$

$$= \max_{\{a_1, z_1, v_1, h_1\}} \mathbb{E}(a_1 + \xi_1 + \alpha\xi_2 - (z_1 + v_1(a_1 + \xi_1 + \alpha\xi_2) + h_1(a_2 + \xi_2 + \alpha\xi_1)))$$

$$= \max_{\{z_1, v_1, h_1\}} \mathbb{E}\left(\frac{v_1+\delta}{c} + \xi_1 + \alpha\xi_2 - (z_1 + v_1(\frac{v_1+\delta}{c} + \xi_1 + \alpha\xi_2) + h_1(\frac{v_2+\delta}{c} + \xi_2 + \alpha\xi_1))\right)$$

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 optimization problem:

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

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:

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

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: $\frac{\mathbb{E}[\boldsymbol{U}] - \mathbb{E}[\boldsymbol{U}^*]}{\mathbb{E}[\boldsymbol{U}^*]} = \delta^2 + 2\delta$