Cooperation and Risk sharing in Public-private Partnerships for the Management of Invasive Species

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Abstract:

Developing incentives for private management efforts for preventing and controlling infectious diseases is a difficult challenge due to its public good nature. Furthermore, since budgets are limited, and the outcomes of prevention efforts are uncertain, resource managers tend to allocate funds to the most immediate and visible problems, often prioritizing post-incursion actions However, there is increasing evidence that focusing on prevention, including early detention and rapid action, is the most cost-effective approach to mitigating the impacts of invasive species. In this paper, we focus on cost-sharing agreements as one of the instruments available for invasive species management, which corrects for the coordination of private biosecurity efforts and encourages early action. We develop a theoretical contract theory framework to understand whether government funds can spread the risk across signatory private agents, and whether agents have incentives to cooperate in biosecurity actions with each other if the compensation mechanism depends not only in one′s actions but on everyone else′s efforts. We find that when the responsibility of biosecurity actions is shared across private agents, funding from the public sector can be used to encourage cooperation, higher private investments in biosecurity, and private agents face lower risk.

JEL codes: H4, J38, L3, Q5

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1. Introduction

The number of introductions is increasing rapidly as a consequence of globalisation of trade and travel, and developing efficient management plans for the prevention and control and invasive species is of key importance to avoid economic, environmental and human health impacts (e.g. Hulme 2009; Simberloff et al. 2012; Pyšek 2012; Perrings et al. 2010; Dalmazzone and Giaccaria 2014). However, designing and implementing such instruments can be proven a difficult challenge, which has led to an increasing literature on the subject in the last decade (e.g. Olson 2006; Gren et al. 2008; Horan and Lupi 2010; Keller et al. 2011).

In economic terminology, policies to manage invasive species are called public goods (Perrings et al. 2002; Perrings et al. 2005). This means that invasive species management is non excludable and non rival, making it challenging to encourage private biosecurity efforts. In addition, invasive species management are driven by many heterogeneous public and private actors, such as seed developers, plant nurseries, pet store dealers, landowners and managers, fishermen, gardeners, agribusiness, urban developers, conservation agencies, those in maritime transport sectors, animal health professionals, etc. Each group has different preferences over management practices and what is an acceptable risk level of incurring an invasion (e.g. Garcia-Llorente 2008; Mills et al. 2011; Humair et al 2014; Reed and Curzon 2015). Reaching an agreeable set of actions towards the control of an invader with such potential heterogeneity of agents becomes challenging (e.g. Liu et al. 2012; Touza et al. 2014; Marzano et al. 2015).

Moreover, the heterogeneity on biosecurity cost, and on the effect that these efforts would have on the invasion threat given the nature of the network links among stakeholders and the mode of invasive species spread, all influence the strategic interactions among agents, and the required level of cooperation among them that can result in an effective policy (e.g. Hennessy 2008). This network of agents interacting with each other is also described to have a weaker/weakest link property, meaning that the success of management efforts depends on the least effective provider (e.g. Burnett 2006; Touza and Perrings 2011). Lastly, there is large uncertainty about ecological, economic and social aspects such as the pathway-level risk, the invader's rate of spread and state of the outbreak, and the impacts, and value of invasion damages. Therefore, identifying the best design of management strategies in the face of limited information remains a critical gap in current understanding (Epanchin-Niell and Hastings 2010; Kriticos et al. 2013; Leung et al. 2015).

The proposed research is designed to evaluate a new policy instrument to manage invasive species, cost/sharing agreements between the government and the private sectors (Waage et al. 2007). However, to date, such plans have only been developed in a few countries, such as Australia, New Zealand, and Galapagos (Anderson 2005). There is increasing interest in contingency plans, specifically on systems of management that will incentivize risk reduction (Defra 2014). In particular, the possibility of implementing cost sharing plans is being evaluated, as expressed in the UK Plant Health Business Plan (2006–2008), and at the

European level by the European Community Plant Health Regime (Food Chain Evaluation Consortium 2010)

The innovation of this policy instrument lies in the 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 contracts thus detail a series of responsibilities that describe how private and public agents should act in order to prevent an outbreak, or to control the spread, but in contracts to voluntary measures these are legal and mandatory by the deeds. Moreover, cost-sharing applies the 'polluter-pay' principle by sharing the invasion damages and control costs. In contrast to the implementation of alternative economic incentives like taxes, which are often not well received by invasion stakeholders citizens (e.g. Knowler and Barbier 2005), the level of financial involvement of those private agents involved in the deed are agreed among the parties.

The instrument also provides the cost-effectiveness advantages of management strategies based on prevention and early actions (Leung et al. 2002; Heikkila and Peltola 2004; Kaiser and Burnett 2010; Sims and Finnoff 2013). But, in general, even these type of management may be limited in their adaptability with regards to unexpected ecological and economic impacts, due to the paucity of biosecurity related information and poor communication between stakeholders (Mumford 2011; Cook et al. 2010; Cook et al 2014; Mauelshagen et at. 2014). However, under cost-sharing, there is the potential for a sense of inclusiveness of all stakeholders involved and a more complete network of support can be developed (Cook et al. 2010). Therefore, cost-sharing can provide incentives for a higher private involvement in biosecurity and surveillance measures, with the potential of improving communication and building public-private trust, gaining information on the status of the outbreak. Moreover, 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 and Duffy 2010).

Lastly, cost-sharing involves preventive plans before outbreaks happen in order to ensure clear responsibilities and funding. This has the additional benefit of being an a-priori agreement, intended to reduce the response time of emergency response, minimizing thus the size and impact of the incursion. It reduces the overall uncertainty for all parties and ensures a minimum level of stakeholder participation (Cook et al. 2010). When an invasion is discovered, the government and the affected industries can quickly respond and begin to work rather than arguing who contributes to what and how much. Furthermore, from the private sector perspective, it could offer an alternative to more restrictive policies (e.g. ban on trade), and spreads the financial potential losses across multiple agents in the sector.

In this paper we study the role of payments from the public sector to encourage responsibility-sharing through private biosecurity actions. The goal is to understand whether government funds can spread the risk across signatory private agents, and whether agents have incentives to cooperate in biosecurity actions with each other if the compensation mechanism depends not only in one′s actions but on everyone else′s efforts. This is studied by developing a theoretical contract theory model of two identical private agents who conduct the biosecurity efforts on behalf of a principal (government), who provides payments to compensate the agents for their actions. We model two scenarios: one where the agents can only invest in management efforts in their own property; and one where private agents can focus part of their actions to collaborate and help the neighbor, thus allowing for the sharing of responsibility of prevention and control actions. The first framework shows how payments that depend on combined biosecurity efforts of both agents can help to spread the risk across everyone in the network, therefore providing theoretical support to why cost-sharing lowers the individual risk of signatory agents. The second framework explores the benefits of sharing responsibilities among private agents, and the role of synergies in biosecurity actions. The results are further evaluated in a numerical exercise, running simulations of how the strategic parameters affect the optimal biosecurity levels and the optimal payments.

The novelty of the paper is two-fold. On one hand, this theoretical framework of risk sharing through payments is the first attempt to model cost and responsibility sharing in invasive species focused on agent′s incentives to develop biosecurity actions and payments for those efforts. On the other hand, it applies a contract theory approach to explore invasive species policy options. Principal-agent models have been traditionally used to study employer-employee situations (see Bolton and Dewatripont 2004 for a general revision), where the employer tries to determine the optimal wages in order to encourage higher productivity from the employee. In our model, we expand the traditional principal-agent model to account for two agents who can cooperate in efforts, similar to the model by Itoh (1991), and the later adaptation by Bolton and Dewatripont (2004). In a similar framework, Holmstrom and Milgrom (1990), evaluate the role of cooperation through explicit collusion among agents. The framework presented here allows agents to help each other directly instead, thus incorporating elements from different previous works.

The paper is structured as follows. The second section introduces the general framework, and some initial results on risk sharing are developed. Section 3 expands the model to allow for responsibility sharing on invasion risk mitigation and cooperation between the two agents. A numerical exercise is developed in Section 4 to compare the results of the two models. Section 5 concludes.

2. Theoretical model of private-public partnerships

2.1. Background

A public-private partnership for the management of invasive species, similar to the Australian Emergency Plant Pest Response Deed (EPPRD), is a formal, legally binding agreement between the government, all state and territory governments and plant industry signatories. The development of such partnerships or deeds involves deciding how to split the costs and responsibilities between the state and the private partners, while at the same time ensuring cooperation among the agents and efficient biosecurity. If an invasion occurs, government and industry parties share the costs based on the potential impacts on public and environmental health, regional and national economies, trade and market access, and control or production costs. Based on where the impacts occur, a specific funding scheme is determined. 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, such as the case of *Phytophthora ramorum*; while Category 4 represents invasions that only damage a particular crop and with no danger of disrupting the economy.

	Gov Funding	Industry Funding
Category 1	100%	0%
Category 2	80%	20%
Category 3	50%	50%
Category 4	20%	80%

Source: Plant Health 2010

Due to the challenges of invasive species management described in the introduction, forming private-public partnerships still remains a challenge (Wagee et al 2007), and most agreements were reached by lying most of the costs (if not all) on the government side (i.e., 100:0 or 80:20).

Since the objective of the paper is to study how risk is shared across agents through payments coming from a signatory agreement, we simplify the cost-sharing model to the case when the government funds all the costs, yet the responsibilities to develop biosecurity efforts fall on everyone in the network. Thus, we leave the study of how to determine the funding ratios for future work, and focus in responsibility-sharing.

We attempt to model the situation described above by using a model of moral hazard with the public sector and two private agents, where the government makes payments to the agents in order to encourage biosecurity actions and to lower the risk faced by private agents regarding invasions. The objective of the framework is to understand how the public sector can harness increased biosecurity measures from private agents by making payments to one agent that also depend on her performance relative to the neighbor.

2.2. Theoretical Framework

The model developed here includes a public entity, who is risk neutral, and who wants to limit the damages an invasion that has potential high social impacts. The public sector provides payments to incentivize private efforts towards surveillance and control. The government receives utility from having a lower invasion impacts, but it must face the costs of the payments to the private agents.

For simplicity, we assume that we have two identical private agents (i, j), who are risk averse. They receive utility from the payments from the public sector for their costly biosecurity efforts. In addition, there is an exogenous random noise that represents the uncertainty of uncontrolled environmental factors that affect the spread and damages of the invasion. Thus, we can represent the state, in terms of invasions, of the managed resource of each individual as follows:

$$q_1 = a_1 + \epsilon_1 + \alpha\epsilon_2$$
$$q_2 = a_2 + \epsilon_2 + \alpha\epsilon_1$$

where q_i is the "quality of the resource" of each agent, with high q_i representing lower invasion levels; a_i are the biosecurity efforts that each agent optimally chooses; and ϵ_i represents the probability of being affected by an invasion. For simplicity, we assume that $\epsilon_{1,2} \sim N(0, \sigma^2)$ i.e. they are independently and normally distributed noises[1]. For example, the case when there the environmental conditions favor the establishment and spread of the invader, $\epsilon_i < 0$ ($\epsilon_i > 0$) so q_i (the quality of the resource) is lower (higher). Lastly, we allow for neighboring effects through the inclusion of a correlation parameter, α. Thus, if $\alpha = 0$, then the state of an agent's resource only depends on his investment in control levels, and his random probability of a damaging invasion; but if $\alpha \neq 0$, then the state of his resource also depends on the external factors conditioning the likelihood of invasion in the neighboring field.

For simplicity, assume that agents have CARA risk preferences, meaning that agents would accept a certain payment (CE) of less, rather than taking the risk and receiving no payments. Assume that the agents have an exponential utility which depends on the costs of their chosen level of biosecurity efforts, and the payments that they get from the public sector:

$$u_i(w, a_i) = -e^{-\eta_i[w_i - \phi_i(a_i)]}$$

where the coefficient η_i represents the degree of risk preferences; and $\phi_i(a_i)$ is the monetary cost of developing invasive species control efforts. Also, assume that costs of control are quadratic on the surveillance and control levels applied:

$$\phi_i(a_i) = \frac{1}{2}ca_i^2$$

In order to model agreement formation, we assume that the payments not only depend on the individual effort, but on everyone's contribution. Therefore the optimal compensation payments depend on all the signatory agents' actions. This is based on the informativeness principle from contract theory, which ensures that when outputs are correlated, it should be optimal to base an individual agent's compensation on both output realizations, as both provide information about an individual agent's action choice. But this modelization can be

[1] For this initial exploration we assume that the probability of invasion is independent of the biosecurity level. We intend to relax this assumption in future work.

rationalized by the public sector wanting to encourage agreeable private engagements on invasion policies.

We assume that the public sector can employ linear incentive schemes, that is, he compensates the agents for their biosecurity efforts, of the form:

$$w_1 = z_1 + v_1 q_1 + u_1 q_2$$
$$w_2 = z_2 + v_2 q_2 + u_2 q_1$$

where z_i are fixed compensation amounts to each of the agents, v_i are variable compensations that depend on the level of invasions in their own area, and u_i are variable compensations that depend on the state of the neighbor's area. For the particular case when the compensation of the government was not dependent on the relative performance, then $u_i = 0$.

Then the role of the government is to develop the correct payments that ensure that agents want to participate in biosecurity efforts, and that their chosen level of management actions is optimal. In this case, since agents are equal (due to symmetry), we can simplify the problem and we only need to solve one optimal scheme(a_i, w_i).

Thus, the public sector will try to maximize his expected payoff in his relation to agent 1, by solving:

$$\max_{\{a_1, z_1, v_1, u_1\}} E(q_1 - w_1)$$

$$\text{Subject to:} \qquad E\left[-e^{-\eta[w_1 - \phi_1(a_1)]}\right] \geq u(\overline{w})$$

$$\text{And} \qquad a_1 \in arg\, max_{\{a\}}\, E\left[-e^{-\eta[w_1 - \phi_1(a)]}\right]$$

That is, the government maximizes his expected benefits (output minus costs of payments to the agent) subject to the participation and incentive constraint of the private agent. The first constraint is the participation constraint, which ensures that the agent wants to participate in the agreement by ensuring that he is at least as well off by participating as he would be on his own (where $u(\overline{w})$ is the utility of the certainty equivalent wealth value, which without loss of generality, we can normalize to 0). The second constraint ensures that the agents are behaving optimally, according to their own incentives.

In order to solve this problem, we can first solve the agent's maximization problem, plug the optimal solution into the participation constraint, and then transform the problem into an unconstrained one.

First we can solve the agent's maximization problem:

$$E\left[-e^{-\eta[w_1 - \phi_1(a_1)]}\right] =$$
$$\mathrm{E}\left[-e^{-\eta[z_1 + v_1 q_1 + u_1 q_2 - \phi(a)]}\right] = E\left[-e^{-\eta[z_1 + v_1(a_1 + \epsilon_1 + \alpha\epsilon_2) + u_1(a_2 + \epsilon_2 + \alpha\epsilon_1) - \phi(a)]}\right] = E\left[-e^{-\eta \widehat{w_1}(a)}\right]$$

By the properties of the lognormal distribution:

$$-e^{E(-\eta\widehat{w_1}(a))+\frac{1}{2}Var(-\eta\widehat{w_1}(a))} = -e^{\left(-\eta(z_1+v_1a_1+u_1a_2-\frac{1}{2}ca_1^2\right)+\frac{1}{2}\eta^2Var(v_1\epsilon_1+v_1\alpha\epsilon_2+u_1\epsilon_2+u_1\alpha\epsilon_1))}$$
$$-e^{\left(-\eta(z_1+v_1a_1+u_1a_2-\frac{1}{2}ca_1^2\right)+\frac{1}{2}\eta^2Var((v_1+u_1\alpha)\epsilon_1+(u_1+v_1\alpha)\epsilon_2))}$$
$$-e^{\left(-\eta(z_1+v_1a_1+u_1a_2-\frac{1}{2}ca_1^2\right)+\frac{1}{2}\eta^2\sigma^2((v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2))}$$

Due to the properties of the exponential function, solving the above problem is equivalent to solving:

$$\max_{a_1}\{\left[z_1+v_1a_1+u_1a_2-\frac{1}{2}ca_1^2\right]-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]\}$$

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

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

Once we have the optimal solution for the biosecurity level from the private agents we can plug it back into the participation constraint:

$$\left[z_1+\frac{v_1v_1}{c}+\frac{u_1v_2}{c}-\frac{1}{2}c\left(\frac{v_1}{c}\right)^2\right]-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]$$
$$=\left[z_1+\frac{1}{2}\frac{v_1^2}{c}+\frac{u_1v_2}{c}\right]-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]=\overline{w}$$

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

$$\max_{\{a_1,z_1,v_1,u_1\}}E(q_1-w_1)=\max_{\{z_1,v_1,u_1\}}E(a_1+\epsilon_1+\alpha\epsilon_2-[z_1+v_1q_1+u_1q_2])$$
$$=\max_{\{z_1,v_1,u_1\}}E(\frac{v_1}{c}-\left[z_1+\frac{v_1^2}{c}+\frac{u_1v_2}{c}\right])$$

Subject to $\left[z_1+\frac{1}{2}\frac{v_1^2}{c}+\frac{u_1v_2}{c}\right]-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]=\overline{w}$

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

$$\max_{\{z_1,v_1,u_1\}}E\left(\frac{v_1}{c}-\left[-\frac{1}{2}\frac{v_1^2}{c}-\frac{u_1v_2}{c}+\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]+\frac{v_1^2}{c}+\frac{u_1v_2}{c}\right]\right)$$
$$=\max_{\{v_1,u_1\}}E(\frac{v_1}{c}-\frac{1}{2}\frac{v_1^2}{c}-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2])$$

We solve the problem sequentially: first, for a given v_1, u_1 is determined to minimize the risk; then v_1 is set optimally to trade off risk sharing and incentives. Therefore, taking first order conditions with respect to u_1 :

$$\frac{\partial}{\partial u_1}\left(\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2]\right)=\frac{1}{2}\eta\sigma^2[2(v_1+u_1\alpha)\alpha+2(u_1+v_1\alpha)]=0$$

Solving for u_1:

$$u_1 = -\left(\frac{2\alpha}{\alpha^2+1}\right)v_1$$

We now substitute this expression into the previous maximization problem and take the first order conditions with respect to v_1:

$$\max_{\{v_1,u_1\}} E\left(\frac{v_1}{c} - \frac{1}{2}\frac{v_1^2}{c} - \frac{1}{2}\eta\sigma^2\left[\left(v_1 + \left(-\left(\frac{2\alpha}{\alpha^2+1}\right)v_1\right)\alpha\right)^2 + \left(-\left(\frac{2\alpha}{\alpha^2+1}\right)v_1 + v_1\alpha\right)^2\right]\right)$$

$$= \max_{\{v_1,u_1\}} E\left(\frac{v_1}{c} - \frac{1}{2}\frac{v_1^2}{c} - \frac{1}{2}\eta\sigma^2 v_1^2 \frac{(1-\alpha^2)^2}{1-\alpha^2}\right)$$

Taking FOC:

$$\frac{1}{c} - \frac{1}{c}v_1 - \eta\sigma^2\frac{(1-\alpha^2)^2}{1-\alpha^2}v_1 = 0$$

Solving for v_1:

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

One result that we obtain is that the optimal level of u_1 , the compensation coefficient for the neighboring state of the invasion is negative when the two agent's outputs are positively correlated, or $\alpha > 0$. This means that a private agent is penalized for a better performance and state of the neighbor's field. This behavior can be rationalized because a good performance by one agent can be due to a high realization of their shock ϵ_2, which also affects positively the state of the field of agent 1. Thus, we can say that both agents' high output is partially due to the shock, or luck. By setting a negative payment, or punishment, the government reduces agent's 1 exposure to a common shock affecting both agents' output level, and thus reduces the variance of agent's 1 compensation. Thus, the reason to introducing payments that depend on both agents' outputs is to filter the common shocks and reducing the exposure to risk.

3. Theoretical Model of Shared Responsibilities

In this section we allow for agent's being able to offer help in terms of biosecurity actions between themselves. This extension evaluates the role of responsibility sharing, and how compensation payments can enhance cooperation and risk sharing.

We extend the model and incorporate one new variable, b_i, which measures the help one agent can provide towards biosecurity levels to the state of the other agent. The rest of the problem still stands as:

$$q_1 = a_1 + b_1 + \epsilon_1 + \alpha\epsilon_2$$
$$q_2 = a_2 + b_2 + \epsilon_2 + \alpha\epsilon_1$$

Assume that the agents have an exponential utility of the form:

$$u_i(w, a_i, b_i) = -e^{-\eta_i[w_i - \phi_i(a_i,b_i)]}$$

where now $\phi_i(a_i, b_i)$ is the monetary cost of developing invasive species control efforts.

Also, assume that costs of control are quadratic on the effort levels applied, and δ measures the substitutability of costly biosecurity actions across agents. Thus if $\delta > 0$, a private agent has an additional cost in not specializing entirely in his own prevention and control measurements and helping the other agent in his tasks:

$$\phi_i(a_i) = \frac{1}{2}ca_i^2 + \frac{1}{2}cb_i^2 + \delta ca_i b_i$$

The incentive schemes are still as in the previous case, given by:

$$w_1 = z_1 + v_1 q_1 + u_1 q_2$$
$$w_2 = z_2 + v_2 q_2 + u_2 q_1$$

Now, the problem of the public sector becomes:

$$\max_{\{a_1,b_1,z_1,v_1,u_1\}} E(q_1 - w_1)$$

$$\text{Subject to:} \qquad E[-e^{-\eta[w_1-\phi_1(a_1,b_1)]}] \geq u(\overline{w})$$

$$\text{And} \qquad a_1, b_1 \in arg\,max_{\{a,b\}}\, E[-e^{-\eta[w_i-\phi_i(a,b)]}]$$

As in the previous case, we first solve the agent's maximization problem:

$$E\left[-e^{-\eta[w_1-\phi_1(a_1,b_1)]}\right]=$$
$$\mathrm{E}[-e^{-\eta[z_1+v_1q_1+u_1q_2-\phi(a,b)]}] = E[-e^{-\eta[z_1+v_1(a_1+b_1+\epsilon_1+\alpha\epsilon_2)+u_1(a_2+b_2+\epsilon_2+\alpha\epsilon_1)-\phi(a,b)]}] =$$
$$E\left[-e^{-\eta\widehat{w_1}(a,b)}\right]$$

By the properties of the lognormal distribution:

$$-e^{E\left(-\eta\widehat{w_1}(a,b)\right)+\frac{1}{2}Var\left(-\eta\widehat{w_1}(a,b)\right)} =$$
$$-e^{\left(-\eta(z_1+v_1a_1+v_1b_1+u_1a_2+u_1b_2-\frac{1}{2}ca_1^2-\frac{1}{2}cb_1^2-\delta ca_1b_1\right)+\frac{1}{2}\eta^2Var(v_1\epsilon_1+v_1\alpha\epsilon_2+u_1\epsilon_2+u_1\alpha\epsilon_1))}$$
$$-e^{\left(-\eta(z_1+v_1a_1+v_1b_1+u_1a_2+u_1b_2-\frac{1}{2}ca_1^2-\frac{1}{2}cb_1^2-\delta ca_1b_1\right)+\frac{1}{2}\eta^2Var((v_1+u_1\alpha)\epsilon_1+(u_1+v_1\alpha)\epsilon_2))}$$
$$-e^{\left(-\eta(z_1+v_1a_1+v_1b_1+u_1a_2+u_1b_2-\frac{1}{2}ca_1^2-\frac{1}{2}cb_1^2-\delta ca_1b_1\right)+\frac{1}{2}\eta^2\sigma^2((v_1+u_1\alpha)^2+(u_1+v_1\alpha)^2))}$$

Solving the above problem is equivalent to solving this:

$$\max_{a_1,b_1}\{\left[z_1 + v_1a_1 + v_1b_1 + u_1a_2 + u_1b_2 - \frac{1}{2}ca_1^2 - \frac{1}{2}cb_1^2 - \delta ca_1b_1\right]$$
$$-\frac{1}{2}\eta\sigma^2[(v_1+u_1\alpha)^2 + (u_1+v_1\alpha)^2]\}$$

From the first order conditions we have that:

$$v_1 - ca_1 - \delta cb_1 = 0$$
$$v_1 - cb_1 - \delta ca_1 = 0$$

And solving for the biosecurity levels:

$$a_1 = \frac{v_1}{c\delta + c}$$
$$b_1 = \frac{v_1}{c\delta + c}$$

If we plug the optimal levels into the participation constraint:

$$\left[z_1 + v_1(\frac{v_1}{c\delta + c}) + v_1\left(\frac{v_1}{c\delta + c}\right) + u_1(\frac{v_2}{c\delta + c}) + u_1(\frac{v_2}{c\delta + c}) - \frac{1}{2}c\left(\frac{v_1}{c\delta + c}\right)^2 - \frac{1}{2}c\left(\frac{v_1}{c\delta + c}\right)^2 - \delta c(\frac{v_1}{c\delta + c})(\frac{v_1}{c\delta + c})\right] - \frac{1}{2}\eta\sigma^2[(v_1 + u_1\alpha)^2 + (u_1 + v_1\alpha)^2] = 0$$

The principal's problem can now be rewritten as:

$$\max_{\{a_1, b_1, z_1, v_1, u_1\}} E(q_1 - w_1) = \max_{\{z_1, v_1, u_1\}} E(a_1 + b_1 + \epsilon_1 + \alpha\epsilon_2 - [z_1 + v_1 q_1 + u_1 q_2])$$

$$= \max_{\{z_1, v_1, u_1\}} \left(\frac{v_1}{c\delta + c} + \frac{v_1}{c\delta + c} - \left[z_1 + v_1(\frac{v_1}{c\delta + c} + \frac{v_1}{c\delta + c}) + u_1(\frac{v_2}{c\delta + c} + \frac{v_2}{c\delta + c})\right]\right)$$

subject to the participation constraint above

Rewriting the problem of the public sector as an unconstrained problem, and taking FOC with respect to u_1 and v_1, we obtain:

$$u_1 = -\frac{2\alpha v_1}{\alpha^2 + 1}$$

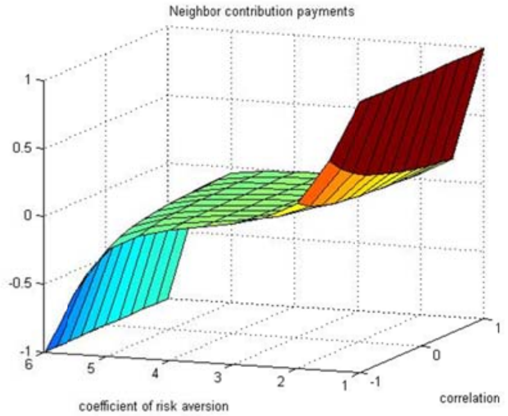
$$v_1 = \frac{2\alpha^2 + 2}{\left((\alpha^4 - 2\alpha^2 + 1)c\delta + (\alpha^4 - 2\alpha^2 + 1)c\right)\eta\sigma^2 + (2\alpha^2 + 2)c\delta + (2\alpha^2 + 2)\, c)}$$

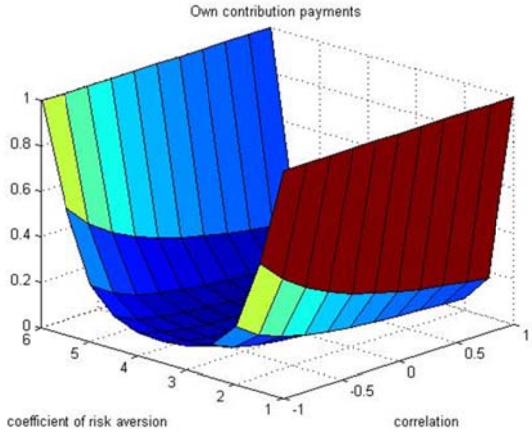
From this conditions, we find that still the main results from the previous section on risk sharing still hold even when we allow for cooperation efforts. If the parameter δ is equal to zero, we go back to the previous case, since there are no gains or benefits for the agents to offer help (they are indifferent about whether to invest in their own private biosecurity or in the neighbor's efforts). For the case when the specialization parameter is different than zero, it plays a role. For a large δ, own and neighboring efforts are lower, to compensate for the extra costs of sharing responsibility.

4. Numerical Exercise

In this section we run a preliminary analysis of the results using a numerical example in order to compare the results of the two frameworks, and how the key parameters affect the optimal biosecurity levels, as well as the optimal payments. The optimal solutions are computed for the following given parameter values:

Correlation parameter	-1 to 1
Mean of noise	0
Variance of noise	1
costs	10
Coefficient of risk aversion	1 to 6





5. Conclusions and further work

One instrument to encourage early coordinated action, which is currently being considered by the European Community Plant Health Regime is cost-sharing (Food Chain Evaluation Consortium 2010). Cost-sharing agreements divide the responsibility of action and damage control between the public and private sector, enhancing cooperation through shared objectives. The innovation of this new scheme lies in the combination of specific agreements on how to prevent and respond to incursions, and the legal commitment to adhere to those plans. Among the key advantages of this instrument is that it develops a sense of inclusiveness of all stakeholders, with the potential of incentivizing risk reduction, gaining information on the status of the outbreak, and improving public-private communication (Cook et al 2010).

In this paper we first studied a novel instrument in invasive species management, and we later attempted to develop the first theoretical framework to evaluates what motivates private participation in biosecurity efforts under responsibility-sharing. The results provide a theoretical foundation for furthering the study of cost and responsibility sharing for invasive species management. This work strengthens our understanding of the conditions in which national biosecurity is best protected through private-public agreements thus providing greater resilience to industries.

In future work to come, we will relax the assumption of symmetry of private agents. When studying the design and implementation of a cost-sharing agreement, an important component will be to develop a theoretical framework that captures the asymmetry of interests between the public and private sector over future expected damages and management costs. In general, the higher the number and variation of stakeholder interests and the higher the social character of the potential impacts (e.g. damage to biodiversity), the more difficult would be to form a cost-sharing agreement (see picture below for the case of plant health in UK). Understanding agent’s differences in preferences towards risks, and costs is crucial for the development of successful private-public partnerships.

Moreover, while cost and responsibility sharing schemes, such as the Australian EPPRD response, are considered one of the most complete and adaptive emergency plans to deal with invasive species, it still has difficulties dealing with new unexpected intrusions (Cook 2011). Currently, the possibility of splitting up the responsibility between the government and industry is limited by the uncertainty surrounding the risk of invasion and the expected high value of invasion damages (Touza et al 2007; Cook et al 2010). An extension of the paper will make the likelihood of the invasion dependent on past biosecurity efforts.

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