PRIVATE RESPONSES TO PUBLIC INCENTIVES FOR INVASIVE SPECIES MANAGEMENT

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ABSTRACT

In this paper the impact of public policies such as subsidies and taxation on invasive species management is explored in a Markov chain process framework. Private agents react to public incentives based upon their long term expected profits and have the option of taking measures such as abatement, monitoring and reporting. Conditions for perverse incentives are derived. The impact of sequencing of taxation and subsides on spread of risks is explored. One key finding of this paper is that excessive regulation may sometimes exacerbate the invasive species problem

Keywords: Invasive Species, Markov process, Perverse Incentives, Taxation and Subsidies.

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INTRODUCTION

It is generally acknowledged that the threat of invasive species cannot be eliminated but that the risks and the potential damages can be reduced considerably through effective management. A key ingredient to the effective management of the risks from invasives is the degree of private participation. However inducing private participation for controlling the invasives could become a major challenge to the policy makers. This is so as private objectives greatly differ from the social objectives, given that private agents do not incorporate the consequences of their actions on society. Further, the limited ability of regulating agents to monitor private agent's actions reduces the choice set and efficacy of such public policies. The difficulty is further compounded when dealing with situations, as is the case with invasive species, where the manifestations of adverse consequences are sometimes far removed from when the action occurred.

A growing concern for policy makers attempting to solicit private participation in the fight against invasives is the prospect of engendering perverse incentives. Perverse incentives provide benefits to the targeted agents from taking measures that are counter productive towards achieving the social objectives. Given the uncertainty over biological parameters related to the pests, and behavioral parameters related to the private agents, (such as degree of monitoring and control efforts) certain policies of the regulating agent (such as compensation for destruction of pest-infested resources) may provide perverse incentives. Figure (1) shows the indemnity payments for various pests by the USDA which have steeply increased over time. Concerns have been raised over the extent of role played by perverse incentives in this increase in payments. Another example where it has been alleged that perverse incentives could have played a role is of the protracted time it took to control the spread of the BSE disease in the UK. While there is no documented evidence to support such claims there, it has been suggested that because the government followed a policy of generously compensating only those farmers whose cattle were affected by BSE or located within the the prescribed eradication region, those who were left out but faced similar loss of market opportunities had an incentive to spread the disease amongst their cattle.

A number of studies exist that have explored the various economic dimensions of managing the invasive species. These include Eiswerth and Johnson (2002), Eiswerth and Van Kooten (2002), McAusland and Costello (2004), Olson, and Roy (2002), Perrings et al. (2000), Settle and Shogren (2002), etc. However, the authors are not aware of any study that delves into the behavioral aspects of inducing or influencing private participation through public policies. Yet, there exists a great need to understand the implications of such public policies both from the point of view of increased demand for public accountability as well as ensuring that the ultimate outcomes are in congruence with what was anticipated.

There are a number of key questions confronting the policy maker while deciding how best to influence private behavior. Foremost is the choice between taxes and subsidies or a combination of both. Due to political considerations and the fact that in most cases it is difficult to assign the blame of pest infestation and spread on private resource owners, public policies so far have mainly resorted to subsidies, thus increasing the chances of perverse motives. In certain cases where farms have been quarantined without any compensation being paid to the farmer, the policy maker has been taken to court over losses from quarantine. Second is related to the extent of effectiveness of such policies in terms of achieving the social objectives. Third is whether such policies induce any further aggravation of the pest problem by providing wrong incentives to the agent.

In this paper we explore all the three questions to a certain extent while primarily focusing on the practicability of the policy implications that emerge from the analysis. In order to achieve this, we model the behavioral risks involved with invasive species management in a Markov chain process framework. The usefulness of this approach has already been demonstrated in ecological modeling literature as it offers a very convenient and transparent way of representing uncertainty evolution through transition probability matrices. Recently some suggestions have been made regarding the utility of Markov chain methods in modeling ecological-economic phenomenon, specifically the invasive species (See Perrings 2003 and 1998).

This paper is divided into two main sections; theoretical framework and numerical simulations. In the theoretical section we briefly discuss the analytical framework and allude to some of the major findings of our investigation. The numerical section puts more structure on the theoretical model and derives some results that are not easily discernible from the theoretical model.

Analytical Framework

Our analysis involves optimization of private economic benefits in presence of taxation and indemnities. The economic benefits, however, are modeled as the long run benefits that accrue from adoption of various levels of monitoring and prevention activities. These long run benefits are derived as a function of the fraction of time private resources spend in each of the various 'states' of infestation ranging from non-infestation to high levels of infestation. Societal welfare may be related to the fraction of time the resources spend in each 'state' as a combined sum of the resource owners' revenues and the impact on the 'rest-of-the-world' from damages that these 'states' may cause in the event of species escaping outside. Optimal monitoring and prevention efforts are first derived under a policy of taxation and subsidies and their impact is explored with respect to the change in societal risks from pests. The role of subsidy in providing perverse incentives in terms of reducing the risks of detection and level of preventive efforts is explored. Unfortunately, public policies are mostly reactive and rarely prepare in advance for pest-infestations. In such a scenario, one key issue of concern is whether regulatory policies can effectively dissuade a resource owner from continuing with his production plan and risk subsequent detection rather than report an infestation at the outset. It turns out that the absolute level of taxation can play a key role in inducing such a behavior. Consequently, threshold level of reporting-inducing taxation is derived. This threshold must also have an upper bound so that the resource owner is not stifled in his entrepreneurial efforts due to a very high level of taxation.

When multiple states of infestation are observable, the regulator has a wider choice of affecting private behavior through a mix of 'carrot and stick' policies. Such policies are often ad-hoc and are either related to economic value of resources concerned or exogenously specified. Under such circumstances, an important question of concern is whether sequencing of taxation and subsidies matters in terms of affecting private behavior. Our analysis reveals that it does matter and some of the harshest policies such as all-out taxation may perform poorly in terms of achieving a low risk of spread of pests as compared to those policies that combine both subsidies and taxation. Surprisingly, it implies that over-taxation can exacerbate the risk of invasive species spread. Such a result is governed by several factors such as the differences in revenue from different states of the resource, risks of detection, abatement costs, etc. under various states of infestation. It highlights the role of key parameters in influencing the dynamics of private decision-making. Similarly, another result emphasizes the fact that an all-out subsidies program may not increase risks as much as a mismatched policy of subsidy and taxation. In the model below we formalize these ideas.

Model

Consider a private resource *R* that yields per period economic returns to its owner at the rate $\pi(R)$. These resources however face the threat of invasion from a certain species (or a class of species) to which the resources serve as a host, thus aiding in their further growth and spread. Upon infestation, the per-period revenues from the resources may decline and are a function of the state of infestation X. Further, the private owner is not the only one faced with this threat of invasion. The pests threaten to spread into a wider region outside the private property thus causing potential economic and ecological damages at a much wider scale. As a consequence, there is a role for public intervention, as the private resource owner has no incentives to consider the threats of spread beyond his resources.

We model the dynamics related with the arrival, control, monitoring, detection and re-growth of species (both hosts and pests) as a continuous time Markov process, which assumes that the inter-arrival time of these events follows an exponential distribution. While a more realistic assumption may be modeling such events as semi-Markov processes, (as they allow for independent allocation of distribution function for events based upon empirical observation) we refrain from such a complication in this paper. Under this framework, the arrival rate of pests is a defined as λ, the control or death rate as δ, the detection rate as *d* and the re-growth of host species following destruction as θ [1]. The Markov chain process is defined by the set of states and the instantaneous rates as described above. The states of the above system are defined as {*R*, *X* and 0}. R is the state before any invasion, X is the invaded state and 0 is the state when the resources of the private agent are completely destroyed due to aggressive public intervention (such as quarantine). The dynamics of the process involving infestation, control and resource destruction and re-growth is shown in figure 2.

Assume that there is a regulator who is able to observe whether the private resources have been infected or not. However, this observation requires some kind of effort on the regulator, and detection is not possible with certainty. That is, detection is probabilistic, with its rate given by *d*. Further, let's assume that the social costs of disease infestation on this private property are high, as a consequence, the regulator is obliged to destroy the host species (which yield economic rewards to the private owner) on the private property.

[1] See Kulkarni (1995) for a discussion of continuous time Markov chain processes. Also, the arrival rate could be an endogenous function of several factors as modeled later on.

The regulator can also choose to compensate the resource owner for the destruction of his resources for the time his resources remain destroyed and thus do not yield any benefits[2]. Also, assume that the resources, once fully destroyed, can be reestablished at the rate θ without any additional costs[3]. Alternatively, resources can grow back instantaneously after a quarantine time distributed with parameter θ. The agent takes into account the long run average revenues and costs of his actions while deciding over level of efforts.

The steady state probabilities of the fraction of time spent in each state, $p(R)$, $p(X)$ and $p(0)$ are determined by using the fact that the rate of arrival and exit from a state must be equal in the long run[4]. From figure 2, this gives us three equations in three unknowns as:

(1) $$p(R)\lambda = p_0\theta + p_x\delta$$

(2) $$p_x\delta + p_x d = p_R\lambda$$

(3) $$p_0\theta = p_x d$$

However, one of the equations is redundant, and therefore we make use of the additional fact that the sum of the fractions of time spent in each states would be one:

(4) $$p_R + p_x + p_0 = 1$$

Solving the above system of equations we can derive the steady state probability values as:

(5) $$p(R) = \frac{\theta(d+\delta)}{d(\lambda+\theta)+\theta(\delta+\lambda)}$$

(6) $$p(X) = \frac{\theta\lambda}{d(\lambda+\theta)+\theta(\delta+\lambda)}$$

and

(7) $$p(0) = \frac{d\lambda}{d(\lambda+\theta)+\theta(\delta+\lambda)}$$

Average expected benefits in the long run would be maximized when the agent sets his objective function as:

Maximize with respect to abatement (*a*) and monitoring (*m*) with costs *c*(*a*) and *c*(*m*)[5]:

[2] There are other forms of compensating the farmer such as direct payments for the value of the destroyed resource, uniform subsidies, etc.

[3] Here, the costs of resource destruction are implicitly accounted for in the amount of time spent in the state 0.

[4] See Kulkarni (1995) for more details on the methodology.

[5] Due to no inter-temporal discounting assumed here, we ignore the lost revenues from being in state 0.

$$\text{(8)} \quad \{\pi(R) - c(m)\} * p(R) + \{\pi(X) - c(a)\} * p(X)$$

First order condition with respect to monitoring and abatement imply:

$$\text{(9)} \quad \frac{dp(R)}{dm}(\pi(R) - c(m)) - \frac{dc(m)}{dm} p(R) + \frac{dp(x)}{dm}(\pi(x) - c(a)) = 0$$

$$\text{(10)} \quad \frac{dp(R)}{da}(\pi(R) - c(m)) + \frac{dp(x)}{da}(\pi(x) - c(a)) - p(x)\frac{dc(a)}{da} = 0$$

The first order conditions with respect to monitoring requires that the marginal increase in the amount of time spent in each of the states be worth their cost in the long run. It is intuitive that if the arrival rate of species is decreasing in preventive efforts, then the expected amount of time spent in the invaded state x would be falling and the amount time spent in the un-invaded state R increasing in monitoring efforts. Note that the rewards from being in any of the states are directly proportional to the time spent in that state. Similarly, the allocation of abatement efforts in the long run is decided by the effectiveness of such efforts in affecting the average time spent in each of the states.

Next, consider the impact of public intervention on private behavior. Upon detection, the regulator has the option of using monetary rewards or punishment. In this simple model without multiple stages of infestation, it is hard to combine both the options simultaneously. Therefore, for now, we assume that the regulator can either offer rewards or taxes upon detection. Under the above assumptions we analyze the impact of public policy on abatement and monitoring efforts. The private agent's new optimization under taxes *t*, can be written as:

$$\text{(11)} \quad \text{Max: } \{\pi(R) - c(m)\} * p(R) + \{\pi(X) - c(a)\} * p(X) - tp(0)$$

Note that besides the taxes, the private owner's costs of being in state zero are also determined by the amount of time spent in that state. This way of modeling taxation makes the costs to the farmer dependent not only upon the detection rate (which is a function of the regulator's efforts) but also upon the biological features of the resources concerned. For instance, if θ is high, the resources would grow back faster thus inflicting less costs to the owner. Alternatively when θ is construed as the rate of elimination of quarantine, the taxes *t* are exogenously specified by the regulator as a function of θ. Modeling taxation this way allows us to incorporate the variations in silvi-cultural aspects of the affected or threatened hosts. Further, indemnity payments that do not cover the full costs of the destroyed resources may also be considered as a form of taxation. The first order conditions with respect to monitoring and abatement efforts can now be derived as:

$$(12)\quad \frac{dp(R)}{dm}(\pi(R)-c(m))-\frac{dc(m)}{dm}p(R)+\frac{dp(x)}{dm}(\pi(X)-c(a))-t\frac{dp(0)}{dm}=0$$

$$(13)\quad \frac{dp(R)}{da}(\pi(R)-c(m))+\frac{dp(x)}{da}(\pi(X)-c(a))-p(x)\frac{dc(a)}{da}-t\frac{dp(0)}{da}=0$$

Note from equation (7) that *p* (*0*) is a function not only of the detection rate *d* and the growth rate θ , but also of the arrival rate of species λ . This is so as the more time the resources spend in the infested state (x), the higher would be the rate of transformation into the resource destruction state (0). As a consequence, the effect of increased monitoring and abatement would be to lower the rate of arrival into state (0). It would be optimal to increase monitoring and abatement as compared to the previous case of no taxation simply because now there is a cost of spending time in the state when resources are destroyed. Therefore, taxation would lead to increased monitoring and abatement, thus reducing the time spent in the state *p*(*x*) too. However, the degree of effect would be governed by several factors. First, as discussed above, θ would play a key role in determining the cost of detection. A higher θ would mitigate the impact of public intervention, as the system would bounce back out of quarantine at a faster rate. Note that an increase in *d*, all else remaining constant, would lead to a reduction in profits by increasing the time spent in the infested state and therefore offer additional incentives to the resource owner towards monitoring and abatement efforts. However, if the average revenues in the infested state do not fall substantially as compared to the un-infested state, the level of taxation that would induce the same levels of monitoring and abatement as before would have to rise, as the costs of spending less time in the infested state are lower in terms of forgone revenues. Consider a special case in which the pests are a nuisance only to the public resources surrounding the private resource, whereas the private resources are not affected by the invasion. In such a case $\pi(X)$ could be greater than $\pi(R)$ if resources grow over time (assuming the arrival rate of invasive species is synchronous with the growth rate of private resource). Now the incentives to reach the state of infestation would be much higher by reducing monitoring and abatement. As a consequence, the level of taxation needs to be increased even further.

The policy of taxation, though effective, may not be feasible under most situations concerning invasive species management. This is primarily because the policy assumes that the regulator has exclusive rights over managing the 'risk of spread' and therefore can stop the private agent from propagating it. However, in most cases the private agent may be the producer of the risk only to the extent that his resources act as hosts to the invading species. Even there the regulator may not be able to pin down the responsibility of spread entirely on the private agent as this issue is entirely different from the case of pollution generating firms that generate pollution as an externality which is directly linked to their production process. In fact, the production function of such firms can be modeled as using pollution as one of the inputs. The contribution of pollution to output in such a case can be considered as positive, whereas in the case of invasive species the generation of species has a negative impact on the output of the resource. This is precisely the reason why the public role in invasive species management so far has been a policy involving all 'carrots' and no 'sticks'. However, with the recent increase in pest infestations and their potential to affect a large section of the economy including both consumers and producers, public policy has been increasingly viewing the risk of farm-related pest spread as the farm owner's liability.

It is obvious that under similar circumstances involving the above analysis, a policy of indemnities instead would lead to opposite behavior on the part of private agents. Both monitoring and abatement would decrease when the regulator subsidizes the resource owner for the destruction of his resources. This is because the higher the payment from such losses, the lower would be the incentive to mitigate the loss through spending more time in the non-infested state (r). Such a policy, though intuitive from the societal welfare perspective, leads to perverse incentives thus causing significant burden to the regulators' exchequer.

Discounting and Socially Optimum taxation

So far we have ignored discounting of future profits and considered the optimal decisions from the standpoint of the private resource owner. However, it is also of interest to explore the role of public policies and factors such as market discount rate, which may be beyond the private decision maker's control. In this section we derive the average expected profits in the long run from starting in various states of the system such as no infestation, infestation or quarantine etc. It may happen that, given the costs incurred from being in various states, the net expected benefits if one starts in the state of infestation are lower or even negative as compared to the non-infestation state. Such scenarios are of crucial interest to the policy maker, who can adjust the costs to the farmers in the infested state in order to dissuade them from going ahead with their production plan in order to reduce the social costs of pests. That is, if the resource owner finds the discounted sum of profits form the repeated cycles of infestation detection and quarantine and back to be negative if his current state is of the infested one, he may chose to report the infestation rather than risk detection and quarantine. The regulator can encourage such actions by offering rewards for voluntary disclosures and punishments for detections.

Following the derivation of average expected discounted costs in Kulkarni (1995), the relation between the generator matrix, per period payoffs in each state and the long run expected profits from starting in each state can be derived as follows[6]:

$$[\ I - Q] \begin{bmatrix} g(r) \\ g(x) \\ g(0) \end{bmatrix} = \begin{bmatrix} \pi(r) \\ \pi(x) \\ \pi(0) = -h \end{bmatrix}$$

The generator matrix Q is derived in the Appendix, g's are the long run expected benefits from starting in each of the three states and the right hand side denotes the per period profits in each state. Assume that the per period profits in the quarantined state are $-h$. We first consider a case when the private decision maker considers the option of whether or not to continue with production depending upon the state of infestation. The decision to stop may be construed as voluntary disclosure of the pests to the regulator. For simplicity we assume the payoffs in each period are net of the optimal abatement decisions given the state of the art in controlling the pests. This allows us to focus upon the role of such costs in affecting reporting decisions. The matrix of G's is derived as:

$$\begin{bmatrix} g(r) \\ g(x) \\ g(0) \end{bmatrix} = \frac{1}{(\theta + \ )(\delta + \lambda + \ ) + d(\theta + \lambda + \ ))}$$

$$\begin{bmatrix} (\theta + \ )(\delta\pi(r) + \lambda\pi(x) + \pi(r)\ \ ) + d(-h\lambda + \pi(r)(\theta + \ ) \\ -d(-\pi(r)\theta + h(\lambda + \ )) + ((\theta + \ )(\delta\pi(r) + \pi(x)(\lambda + \ )) \\ \delta\theta\pi(r) + \theta\lambda\pi(x) - h\delta\ \ - h\lambda\ \ + \theta\pi(r)\ \ - h\ ^2 - d(-\theta\pi(r) \\ + h(\lambda + \ )) \end{bmatrix}$$

The critical level of discount factor below which it becomes optimal for the private agent to stop production and report infestation is derived by solving for $g(\pi(x)) = 0$ as:

[6] See Kulkarni (1995) pgs. 306-11 for more details

$$= \frac{dh - \delta\pi(r) - (\theta + \lambda)\pi(x) + \sqrt{(-dh + \delta\pi(r) + \theta\pi(x) + \lambda\pi(x))^2 - 4\pi(x)(-dh\lambda + (d\theta + \delta\theta)\pi(r) + \theta\lambda\pi(x))}}{2\pi(x)}$$

Next we explore the optimal tax rate (given the private agent's discount rate) that would make the reporting decision beneficial, and stopping optimal. This is achieved by inducing a per period tax rate t in the infestation state X. Note that in addition to the costs of quarantine etc. incurred in the state of detection, this tax rate is charged based upon the time spent in state X. That is, the regulator punishes the private agent on the principle that the amount of time spent in state X would have a proportional impact on the social costs of infestation due to its spread outside the region. This optimal threshold of taxation using similar analysis can be derived as:

$$t = -dh\lambda + \{d\theta + \delta\theta + \delta \quad\}\pi(r)$$
$$+ \{\theta\lambda + \theta \quad + \lambda \quad + \quad ^2\}\pi(x) - dh$$
$$\div (\theta + \quad)(\lambda + \quad)$$

Any taxation beyond the above level of threshold makes the private agents profits negative from starting in the state of infestation and continuing without reporting. The taxation threshold for a hypothetical set of parameters is shown in figure 3.

There is a great deal of significance to knowing such a threshold level of taxation. Most policies for invasive species control are reactive in nature and are introduced when pests have already infested or seriously threaten to infest a neighborhood surrounding the private resource (which is believed to be harboring them). Under such a situation, the regulator has no knowledge of the actual scenario and would need to select his taxes such that they are neither too low so that the private owner has no incentive to stop when he is infested and would prefer the risk of detection, nor too high so that private enterprise is not severely stifled. This optimal level of taxation must lie between these two extremes.

Two States of Infestation and Sequencing of Taxes and Subsidies

One interesting issue of policy interest is whether the sequencing of taxation and subsidies matters. More specifically, under what circumstances is it optimal to tax first and subsidize later or subsidize first and tax later, or either tax or subsidize only. This section extends the above model to a more general case involving more than one state of infestation. In particular, we look at two states of infestation *X* and *Y*, where the state *Y* is a transition from *X* and involves higher levels of infestation. It may be assumed that the chances of detection are higher at higher levels of infestation. Further assume that detection in the state *X* leads to total loss of resources but with an indemnity payment of *l* through transition to the quarantined state (*l*) and detection in state *Y* leads to an indemnity payment of *h* through transition to the quarantined state (*h*). The rate diagram is shown in Figure 4.

The regulator could make one of the states less desirable than the other by reducing the relative indemnity payment of one state with respect to the other or even making it negative. In order to simplify things, let us assume that the risk of spread to a higher state, given by λ, is exogenously determined, and the only thing the resource owner can control is the level of his abatement efforts. Expected profit maximization problem of the resource owner could be stated as:

(14) Max:

$$\pi(R) * p(R) + \{\pi(X) - c(x,a)\} * p(X) + \{\pi(Y) - c(y,a)\} * p(Y) + l * p(l) + h * p(h)$$

First order condition with respect to abatement effort gives[7]:

[7] The derivation of the steady state probabilities is provided in Appendix A.

(15)

$$\frac{dp(R)}{da}\pi(R) + \frac{dp(x)}{da}(\pi(X) - c(x,a)) - p(x)\frac{dc(x,a)}{da} + \frac{dp(y)}{da}(\pi(y) - c(y,a)) - p(y)\frac{dc(y,a)}{da} + \frac{dp(l)}{da}l + \frac{dp(h)}{da}h = 0$$

In order to study the effect of sequencing of taxes and subsidies we compare the fraction of times the system spends in each state under different policies. This would give us an idea over the extent of externalities generated. For instance, the higher the time spent in state *Y*, the higher may be the risk of spread into neighboring areas as compared to the time spent in state *X*.

Consider a policy of equal subsidies in both the states *X* and *Y*. Some interesting sub cases (A1-A4) may be considered:

A.1

$$l = h \ \& \ \pi(y) > \pi(x) \Rightarrow p(y) > p(x)$$

A.2

$$l = h \ \& \ \pi(y) > \pi(x),\ d(x) < d(y) \Rightarrow p(y) \ ? \ p(x)$$

A.3

$$l = h \ \& \ \pi(y) < \pi(x),\ d(x) < d(y) \Rightarrow p(y) < p(x)$$

A.4

$$l < h \ \& \ \pi(y) < \pi(x),\ d(x) < d(y) \Rightarrow p(y) \ ? \ p(x)$$

A.1 may occur when the pests do minimal damage to the hosts and most of the damages from them are to the neighboring areas outside the private resource owner. It may also happen when state *y* also implies a higher level of resources, i.e. the resources grow over time and the higher state of infestation may be possible only with a higher level of resources. In such a case as long as the resources yield more revenues net of damages from higher level of infestation, $\pi(y) > \pi(x)$ would imply that in the long run the resource owner would have an incentive to keep his resources in the state *y*. A.2 on the other hand is the same as A.1 except that an additional assumption is made related to the chance of detection being higher in the higher state of infestation. Now it is ambiguous whether the system would still spend more time in state *y* as it would be determined by the parameters of the model. Perhaps with less time spent in state *y*, one could make up as much revenues as one makes with more time in state *x*. However, we have not made any assumptions about the rate of regeneration back into state *R*. It may happen that the regulator enforces a higher level of quarantine (for instance, number of years required to spend as fallow land before replanting) if the detection occurs in state y. This assumption can be easily incorporated in the differentiation of subsidies or taxes. The third sub case, A.3 is obvious as with higher level of detection and lower level of profits in state y, it is less profitable to spend more time in it. Finally, when indemnities are based upon the stock of infestation, even lower revenues in state *y* can provide incentives to spend more time in that state. This is shown in case A.4. There are a number of other sequences involving various combinations of taxes and subsidies of interest and as intuition would suggest it is hard to predict the exact outcome unless all the information is available related to the parameters involved. In the following section we explore some specific cases with the help of a numerical example to gain further insights.

A Numerical Example

In order to test our intuition we perform some numerical simulations using a set of hypothetical numbers. Additional assumptions need to be undertaken regarding the shape of the cost and revenue functions. We assume non-linearity in the costs of abatement and effectiveness of control measures with respect to pest mortality. The specific functional forms and parameter values are presented in Tables 1 and 2 in Appendix B. Figure 5 shows the value function of the resource owner under optimal policy, which is convex.

His task is to select the optimal levels of abatement in the two infestation stages in order to maximize his long run expected value. Next, we do some simulations by changing the parameters of the model to see their effects on the optimal abatement efforts and the steady state levels of the probabilities, which are of relevance to the regulator. These simulations are shown in two sets through tables 3 and 4. We consider a case where the revenues to the resource owner from all the three states are the same. This assumption is made in order to highlight the impact of public policy on private managers by neglecting the impact of lower revenues in the infested states. However, the consequences of differential revenues should be obvious once the implications from the general case are derived. In table 3 we also fix the arrival rate of species to be exogenous and unvarying with the state of infestation, which is relaxed in the later set of simulations. Finally, the rates of detection too are unvarying with the levels of infestation. First case in table 3 highlights the policy implications of a uniform taxation policy in both the states of infestation. Notice that the fraction of time spent in state *x* is much higher as compared to state *y* despite the revenues in the two states being similar. This in fact is true for all the cases in table 3. This has to do with the fact that whereas the arrival rates of species are constant amongst the states, the only way to reach state *y* is through *x*. On the other hand, state *x* could be reached through both *r* and *y*. When there are subsidies in state *y* and taxation in state *x* (case two), the fraction of time spent in state *y* increases marginally. However, the fraction of time spent in state *x* too increases, as that is the only way to influence higher arrival rates in state *y*. This detail was not readily intuitive through the theoretical analysis above and could be of high significance for policy purposes, as it highlights the specific linkage effect between states. In cases when the social risks posed by state *y* are only marginally higher than the risks posed by state *x*, this policy would backfire as the fraction of time spent in *x* increases despite taxation in *x*. Without understanding this interlinkage, however, one may vouch for a policy of early taxation combined with later indemnities thus producing inefficient outcomes.

Further, notice that abatement falls in state *x* and is zero in state *y*. In this case the higher risks from being in state *x* are compensated by the reduced abatement costs and the higher benefits from being in state *y*, which yields rewards through detection in state *h*. In the third case, when state *y* is taxed and state *x* rewarded, time spent in *x* increases and *y* decreases, which should be obvious. Notice, that the time spent in the non-infested state (*r*) is highest in this case and the risk of spread to outside areas the least[8]. Finally,

[8] We have assumed that the risks of disease spread are highest in state y, which is of major policy concern to the regulator.

subsidies in the two states yield the highest amounts of time spent in the infested states and the least amounts of time spent in the non-infested one.

So far, the results are very obvious. However, now allowing for more reality we relax the assumptions of uniform levels of arrival and detection rates in the two infested states. Besides, we also assume that the amount of time spent in the detection states (*l* and h) is much higher, which is given by the lower levels of departure rate out of these states[9]. The results of the new set of simulations are demonstrated in table 4 in the Appendix. First, notice that with an increase in arrival and detection rates in state *y*, the fraction of time spent in state *y* is uniformly higher than x all through out. Further, the revenues are uniformly lower as the system spends more time in the detected states, which yields much lower (10 compared to 90) revenue. Notice two striking results from these sets of simulations. A policy of uniform taxation in both states (case 1) does not yield the lowest levels of risk in state y and a policy of uniform subsidies (case 4) does not produce the highest levels of risk in the higher infested state *y*. Let's explore the case of taxation first. The lowest level of risk in fact is attained when the regulator follows a policy of subsidizing the lower infested state and taxing the higher infested state (case 3). When *y* is taxed and *x* is subsidized, the abatement efforts in state *x* are lower and state *y* are higher as compared to the case when both the states are taxed (case 1). In case three, it pays to spend less time in Y by abating more. Notice that higher abatement in Y also increase the rate of arrival into state X which is now more beneficial compared to case 1. Lower abatement in state *x* serves two purposes. It increases the fraction of time spent in state *x* directly and also indirectly through a higher detection rate in state *l*. Note that the later purpose is even more beneficial as it increases the time spent in state *r*, which yields the most rewards. Whereas, it pays to increase abatement marginally in state *y* as it increases the arrival rate back into state *x* and consequential bouncing back to states *r* via *l* while simultaneously lowering the costs of abatement efforts. Note that the reduction in abatement efforts in state *x* in case 3 has a higher impact on steady state probability of state *l* as compared to state *y*. Similarly, abatement effort in state *x* has a higher impact on the steady state probability of state *y* than the impact of abatement effort in state *y* itself. As a consequence, time spent in state *l* increases and that in *y* decreases.

Similar analysis will explain the anomaly in the case when uniform subsidization yields lower risks in state

[9] This can be rationalized as the increase in quarantine time that the detected farm is required to spend before resuming production.

y than a policy of taxing state *x* and rewarding state *y*. Note that under uniform subsidies in both states (case 4), the amount of time spent in the non-infested state is lower than that under case 2. In case 2 taxation in state 2 leads to higher abatement efforts in that state. However, in order to make up for the loss of revenues, abatement effort in state y falls too relative to state 4. This ensures that the time spent in state *y* and *h* are higher than before, thus leading to societal risks.

To recoup the assumptions that make this kind of result possible: 1. Owners' resources remain unaffected by pests and the only threats are to the outside world. 2. Rate of further infestation increases when stocks are already infested. 3. The detection rates are higher in the higher state of infestation. 4. The level of subsidies and taxation is exogenously specified (which may be related to the level of resources or other factors). 5. Abatement costs are non-linear and increasing in abatement. 6. Death rates are non-linear and increasing in abatement efforts.

When assumption 1 is relaxed it is possible that results change if there are higher losses associated with higher levels of infestation. However, it is the difference in the relative revenues in the three states that will determine the shape of the outcome combined with the other parameters that played a key role above. For instance, even when reducing the level of revenues in state *y* to 80 while keeping others constant, the same results follow as above.

CONCLUSION

A number of results come out of the above analysis. First, the single state of infestation model derives the condition for optimal abatement and monitoring efforts of the private resource manager when only the long run expected rewards are considered. Private efforts are affected not only by the biological parameters such as the arrival and death rates of species, but also by the expected revenues in the various states. The regulator can affect both of these factors through his policies. For instance, the length of quarantine would determine the time the resources will yield no or negative profits. In order to achieve a socially optimal level of risk of spread (given by the fraction of time spent in the higher state of infestation *Y*) the optimal tax rate must incorporate the above parameters as shown in case with optimal taxation under discounting. The threshold level of taxation is higher when the revenues in state *Y* are higher, and is lower when the arrival rate of species is higher (Figure 3). The second result may seem counter intuitive, but note that under a higher arrival rate of species the private resource owner has lower profits. Finally, the numerical examples highlight interesting cases where sequencing of taxation and subsidies may yield different levels of risks of spread. This is an important issue for policy-making purposes as the regulator often has to decide about the correct way of providing both and carrots and sticks so that minimum perverse incentives are generated. It is even more important under situations where little information is available over the biological parameters or the profit function of the private agents. Under such a situation it may not be possible to design an optimal level of taxation and subsidy policy. As a consequence, regulators resort to fixed or lump sum payment or taxation schemes like the ones chosen in the examples.

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APPENDIX A

In order to solve for the long run steady state probabilities of the states we need to make sure that the rate of exit from a state is the same as the rate of entry into it. For instance, as shown in figure 2, the rate of exit from state R is given by $p(R)\lambda$, where as the rate of entry into it is given by $p(x)\delta + p(l)\theta + p(h)\theta$. Using similar logic we get five equations corresponding to the five states as below:

(16) $p(R)\lambda = p(x)\delta + p(l)\theta + p(h)\theta$

(17) $p(x)\delta + p(x)\lambda + p(x)d = p(R)\lambda + p(y)\delta$

(18) $p(y)d + p(y)\delta = p(x)\lambda$

(19) $p(l)\theta = p(x)d$

(20) $p(h)\theta = p(y)d$

However, one of the equations above will be redundant, and therefore, we also make use of the fact that the sum of the fraction of times spent in each state must equal 1:

(21) $p(l) + p(h) + p(x) + p(y) + P(R) = 1$

Using the above equations the steady state probabilities can be solved as:

(22)
$$p(h) = \frac{1}{\left\{\theta\frac{d+\delta}{d\delta} + \frac{d+\delta}{\lambda} + 1 + \frac{\theta}{d}\right\} + \left\{\frac{\theta(d+\delta)}{\lambda^2\delta}\right\}\left\{\lambda + d + \delta - \frac{d\delta}{\delta+\lambda}\right\}}$$

and

(23)
$$p(l) = \frac{(d+\delta)}{\left\{\left\{\theta\frac{d+\delta}{d\delta} + \frac{d+\delta}{\lambda} + 1 + \frac{\theta}{d}\right\} + \left\{\frac{\theta(d+\delta)}{\lambda^2\delta}\right\}\left\{\lambda + d + \delta - \frac{d\delta}{\delta+\lambda}\right\}\right\}\lambda}$$

(24)
$$p(x) = \frac{(d+\delta)d}{\left\{\left\{\theta\frac{d+\delta}{d\delta} + \frac{d+\delta}{\lambda} + 1 + \frac{\theta}{d}\right\} + \left\{\frac{\theta(d+\delta)}{\lambda^2\delta}\right\}\left\{\lambda + d + \delta - \frac{d\delta}{\delta+\lambda}\right\}\right\}\lambda\theta}$$

(25)
$$p(y) = \frac{\dfrac{1}{\left\{\theta\frac{d+\delta}{d\delta} + \frac{d+\delta}{\lambda} + 1 + \frac{\theta}{d}\right\} + \left\{\frac{\theta(d+\delta)}{\lambda^2\delta}\right\}\left\{\lambda + d + \delta - \frac{d\delta}{\delta+\lambda}\right\}}\theta}{d}$$

(26)
$$p(R) = \frac{\dfrac{1}{\left\{\theta\frac{d+\delta}{d\delta} + \frac{d+\delta}{\lambda} + 1 + \frac{\theta}{d}\right\} + \left\{\frac{\theta(d+\delta)}{\lambda^2\delta}\right\}\left\{\lambda + d + \delta - \frac{d\delta}{\delta+\lambda}\right\}}\theta(d+\delta)}{\lambda d\delta}(\lambda + d + \delta - \frac{\lambda\delta}{\delta+\lambda})$$

APPENDIX B

Table 1: Functional Forms

$\delta(x) = a(x)^2$; $\delta(y) = a(y)^2$; $c(x) = a_0 a(x)^3$; $c(y) = a_1 a(y)^3$

Table 2: Base Case Parameters

$\pi(r)$ =90; $\pi(x)$=50; $\pi(y)$=25; l=10; h=10; a0=1; a1=1; λ =2; d=3; θ =15;

Table 3: $\pi(r)$ = 90; $\pi(x)$ =90; $\pi(y)$ =90; a0 = 1; a1 = 1; λ ≩ 2; d = 3; θ ≩ 15;

	A (x), a (y)	Revenue	P (x)	P (y)	P (r)	P (l)	P (h)
L = -10, H = -10	2.1, 0	83.65	.149	.099	.702	.029	.02
L = -10, H = 10	2, 0	84.05	.154	.103	.692	.031	.021
L = 10, H = -10	2, 1	84.3	.165	.083	.703	.033	.017
L = 10, H = 10	1.75, 0	84.7	.166	.111	.668	.033	.022

Table 4: $\pi(r)$ = 90; $\pi(x)$ = 90; $\pi(y)$ = 90; a0 = 1; a1= 1; $\lambda(x)$ = 2; $\lambda(y)$ = 50; d (x) = 3; d (y) = 5; θ ≩ 5;

Cases	Conditions	a(x), a(y)	Revenue	P (x)	P (y)	P (r)	P (l)	P (h)
Case 1	L = -10, H = -10	6.29,1.65	71.1	.0192	0.1245	0.7203	0.0115	0.1245
Case 2	L = -10, H = 10	25.4, .9	73.9	.0177	0.1526	0.6665	0.0106	0.1526
Case 3	L = 10, H = -10	6.21, 1.74	71.3	0.0198	0.1236	0.7211	0.0119	0.1236
Case 4	L = 10, H = 10	5.34, 1	74	0.0182	0.1519	0.6670	0.0109	0.1519

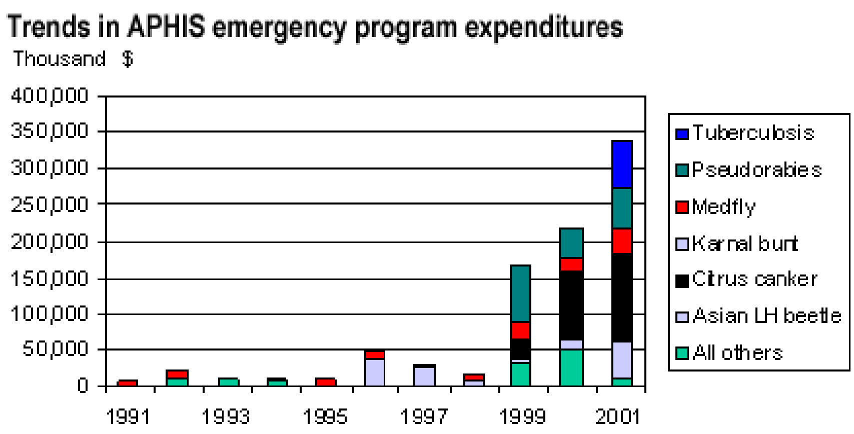


Figure 1: **Invasive Species Management: Trends in Emergency Program Expenditures, USDA Briefing Room**

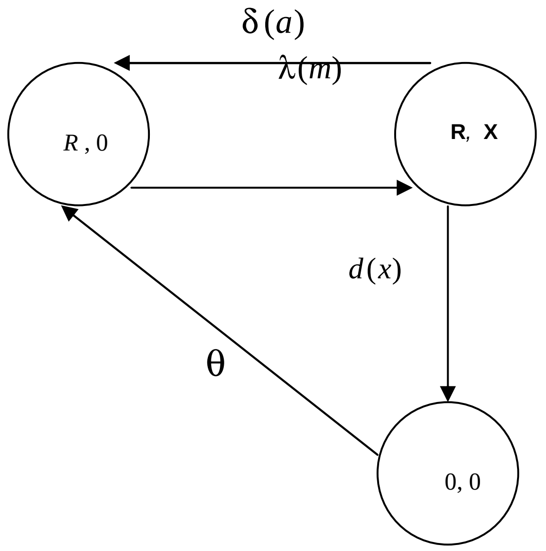
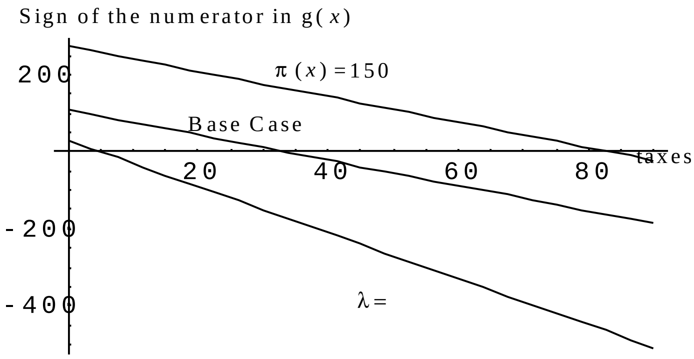


Figure 2: Rate Diagram for the One Infestation State Case



$\pi(r)$ =150; $\pi(x)$ =100;h=10; λ =5;d=10; δ =2; θ = .1;   = .5;

Figure 3: The threshold level of taxation under various scenarios

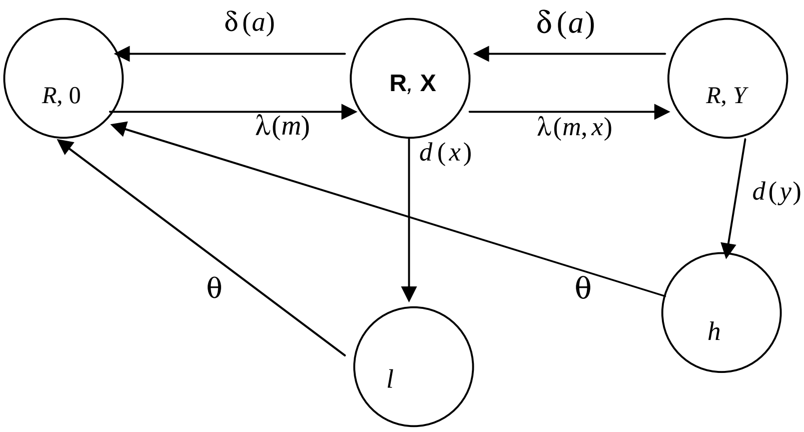


Figure 4: Rate Diagram: Double Infestation States

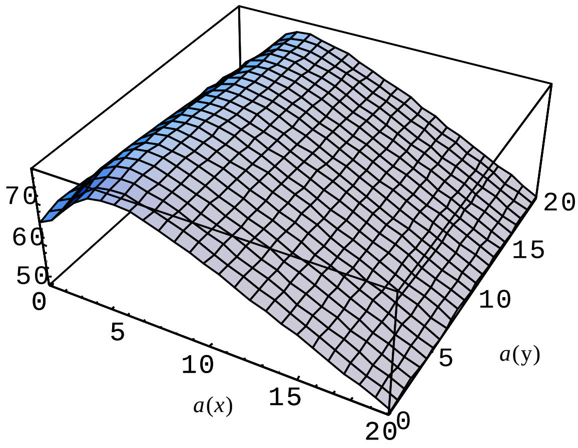


Figure 5: The value function for the private resource owner in the base case