Title: Introductions of invasive species: Failure of the weaker link

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Abstract

The prevention of invasive species is modeled as a "weaker link" public good. Under the weaker link aggregation technology, individual contributions beyond the lowest level will still provide benefits, but progressively these benefits decline as contributions exceed the minimum. A two-region model is constructed, assuming incomplete information concerning costs of provision. We compare the results of the model to several benchmarks in order to gain insights regarding what we can expect countries to contribute to this transnational public good and how these contributions differ from the Pareto optimal level, given the technology and information structure of this special type of public good.

I.   Introduction

The prevention of invasive species can be described as a special kind of public good. Preventative measures in one region of the world lowers their risk of invasion by nonnative species. Less chance of invasion in one place may mean less chance of invasion in others, particularly if the regions share a border or engage in heavy trade. For example, had *Dreissena polymorpha* (Zebra Mussels) been prevented from entering the Great Lakes, and spreading down the Mississippi River, they may not have invaded large southern and eastern portions of the United States. Or if *Centaurea solstitialis* (Yellow Star Thistle) had been prevented from moving from Chile to California to Oregon, it might not be covering most of the country as it does today.

Several authors (Conybeare et al. 1994, Vicary and Sandler 2002, Perrings et al. 2002) have described the prevention of invasions as being characterized by a "weakest link" public good technology. That is, the overall level of prevention in the world is determined by the weakest contributor, or the region that provides the least prevention. This would imply that zero prevention by one country results in zero effective prevention for the world. Because this should not be the case in general, we model the prevention of invasive species as a "weaker link" public good. With weaker link public goods, lower investments by others diminishes returns of those who invest more, but those who invest more may still be better protected than those who invest less.

The specific question we address in this work concerns the level of prevention regions will contribute given the nature of the "weaker link" public good. Our interest lies in how equilibrium contribution levels will compare to the socially optimal level under two distinct information structures. We purposefully abstract away from significant elements to this problem, notably the type of prevention activity being executed, regions' preferences and income levels, and the probabilities of invasion. Our focus herein is on the level of individual contribution to the weaker link public good in a two-region setting.

The objectives of this paper are as follows. First, we will argue that the prevention of biological invasions is indeed characterized by a weakest link-type technology. A static two-region model of provision to the public good of prevention is developed, assuming incomplete information concerning the other's costs of provision. We compare the results of the model to several benchmarks in order to gain insights regarding, one, what we can expect regions to contribute to this transnational public good, and two, how these contributions differ from what should be provided, given the technology and information structure of this special type of public good.

The rest of the paper is organized in the following manner. Section II continues the description of weakest link public goods, and characterizes the prevention of invasive species as a more general category of public goods. Relevant literature is reviewed in Section III. Section IV introduces the 2-region model and illustrates its implications for individual provisions through a short numerical example. The efficient level of prevention under the weaker link technology is developed as the benchmark case in

Section V. Section VI characterizes prevention assuming complete information under the weaker link technology. The most realistic specification, the provision of invasive species prevention under incomplete information, is modeled in Section VII. Section VIII provides ex ante comparisons of contribution levels derived under each specification, Section IX goes through an ex post comparison exercise, and Section X discusses policy implications and concludes.

II.   Weakest link public goods

The prevention of invasions can be described as a (impure) public good due to its substantial degree of nonrivalry of benefits and nonexcludability of beneficiaries. Failure to halt an invasion at one border puts other regions at risk. For example, the state of Hawaii benefits from the continental United State's diligence in control and treatment of mosquitoes, potential vectors for the West Nile virus. To date, Hawaii is one of only three U.S. states free of this virus, largely due to California-based efforts to control their own mosquito population. Furthermore, California cannot preclude Hawaii from reaping these external benefits, resulting in a nonexcludable dimension to the prevention of invasive species.

However, preventing the introduction of unwanted organisms is a special type of public good. Regardless of how sophisticated a particular region's technology to thwart invasion, if other regions have little or no measures in place, the diligent region's efforts

to keep invasives out will be reduced. This may have important implications for individual investments in invasive species prevention, as high levels of expenditures in one region do not imply high levels of effective prevention. Each region's ability to prevent biological invasions is therefore determined by the regions with the weakest prevention technologies.

Weakest link public goods assume that every agent's contribution to a public good will only return benefits associated with the smallest contribution. This type of venture will depend on the integrity of the whole and will be only as strong as its weakest contributor. The classic example was given by Hirshleifer (1983), in which the lowest section of a levee determines the flooding danger for the entire island. Preventative measures by a region against biological invasions include mechanisms such as inspections at incoming ports, irradiation, quarantine, restrictions on imports, etc. Even with the most stringent of policies, however, the probability of introduction remains above zero. Microscopic organisms and concealed hitchhikers make the complete reduction of risk impossible. The best regions can do is reduce the probability of the successful establishment of an unwanted organism by investing in some level of prevention. When regions decide how much to invest, they identify perceived threats from outside, and consider their costs of minimizing these threats. The benefits that accrue from these individual decisions, however, are a result of more than their own investment decision. The benefits will accumulate according to some function of all of the regions' individual decisions. One way of modeling this phenomenon is through the weakest link public goods model.

The focus herein will be on unintentional introductions of invasive species[1]. Preventing introductions of invasive species is complicated by the benefits of globalization and increased traffic throughout the world. A couple of regions have advanced technologies for dealing with these issues, in particular Australia and New Zealand. However the transfer of unwanted species onto new land masses requires efforts by not only the region attempting to prevent the introduction, but mutual efforts by all regions that have any sort of direct or indirect relation with it.

Consider the weakest link technology in which the total level of public good is identical to the smallest provision of the contributors. Even if several regions adopt highly sophisticated levels of preventative technology, if one region does not even attempt to prevent, then every region would experience the level of protection associated with doing nothing at all. While this is possible, this is not likely to be the case in general. Because the contributing region's efforts may not necessarily be reduced to zero, we will consider a less severe class of public goods of the *weaker* link variety.

Although one region develops a highly rigorous inspection system, and other regions have less strict mechanisms in place, the first region will still benefit from their advanced systems. Nevertheless, such a region still has a prevention problem to contend with, owing to the lax prevention by its neighbors. For this category of public goods, the weaker link variety, the smallest contribution has the largest marginal influence on utility, followed by the second smallest contribution, etc. (Arce and Sandler 2001). Individual contributions beyond the lowest level will still provide benefits, but progressively these

benefits decline as contributions exceed the minimal one. A region that fails to provide adequate protection from invasive species may impose significant costs on other regions, reducing returns to more intensive prevention programs in place by others.

The weaker link technology is particularly useful for describing prevention efforts for certain types of species and between certain kinds of locations. Species that fall under this prevention technology include unintentional introductions that arrive in their new area as stowaways (hidden or concealed on people or in goods or cargo) or are otherwise accidentally moved from one place to another. The weaker link technology is appropriate when the regions have the following characteristics: shared borders, heavy movement of people and cargo between places, and perhaps most importantly, once one of two places gets a species, the probability that the other gets it as well increases greatly (so that prevention in both places matters).

Two examples are illustrative. First, take two island communities, Guam and Hawaii. *Solenopsis invicta*, the Red Imported Fire Ant (or RIFA) has not established in either place, although arrival seems imminent. RIFA has established itself both to the west and to the east of these two locations, including many parts of Asia and Australia, and the in the continental United States. RIFA is transported through the movement of travelers and goods as a stowaway species. Heavy traffic between Hawaii and Guam, and the fact that RIFA would certainly be an unintentional introduction makes the prevention of RIFA in these two locations a weaker link problem. The less prevention Hawaii does, the worse off Guam is. Likewise, the more Hawaii does, the better for Guam, and vise versa.

Another example is between the states of Florida and Georgia. Both states have a vested interest in preventing the establishment of Zebra mussels (*Dreissena polymorpha*) in their waters. Zebra mussels have made it all the way from their native Caspian Sea region to The Great Lakes region, down through the Mississippi River, and as far as south as New Orleans, LA. The mussels are not only moved through adjoining water bodies, but also through overland transport on trailored boats. This has been documented as far west as California and Washington, among other places. With many of the waters in the southern states occupied by mussels, prevention investments Georgia makes, such as increased monitoring and boat inspections, will help prevent entry into Florida, and vise versa.

In the preceding examples, both of the regions involved hope to prevent an invasion, and are reliant on their neighbor being diligent in their prevention activities as well. Once Hawaii gets RIFA, or Georgia gets mussels, it is only a matter of time before Guam or Florida becomes invaded as well. Weaker link technology is appropriate since doing more helps my neighbor, while doing less hurts them.

III.   Previous literature

The orthodox pure public goods model assumes only regularity and convexity of the production function (Samuelson 1954). However many models also assume that each individual consumes a quantity of public good defined as the sum of all individuals' contributions to that good (e.g., Chamberlin 1974, Cornes and Sandler 1984, Bergstrom

et al. 1986). Hirshleifer (1983, 1985) extended the analysis of public goods to include

models that do not fall into this class of production functions. He separates the analysis

into three cases. First, the common "summation model," given by $Q = \sum_i q_i$, where q_i

denotes individual i's contribution to the public good, and Q is the total provision of the

public good. There are then two extreme cases, the weakest link model, $Q = \min_i q_i$ and the

best-shot model, $Q = \max_i q_i$. In the first extreme case, the total quantity available to each

agent equals the smallest individual contribution, and at the other extreme, the total

quantity available to each agent equals the largest individual contribution. Hirshleifer

shows that underprovision (equilibrium contributions vs. efficient contribution levels)

disappears in the weakest link case and is more severe under the best-shot model, as

compared to the standard summation case. Hirshleifer (1984) then extended his definition

to include another form of social composition functions, the more general case involving

weights w_i, in which

$$Q = \sum_i w_i \, q_i \text{ where } w_i = 1 \text{ for the smallest } q_i, 0 < w_j < 1 \text{ for the larger } q_j's$$

This function puts full weight on the minimum contribution and fractioned weights on

any larger contributions. As expected, Hirshleifer finds that equilibrium provision will

approach the efficient level as the weights approach the weakest link condition. This

weighted sum case was later developed into the weaker and better link models.

Several functional forms have been offered to describe the weaker link technology. Following Hirshleifer, Mueller (1989, p.23) considers the following formulation in an example of the two-agent weaker link public good case:

$Q = q_1 + w q_2$, $q_1 \leq q_2$, $0 \leq w \leq 1$. If $w = 0$, we have the weakest link case, and $Q = q_1$, the smaller of the two contributions. The larger w is, the more 2's contribution beyond 1's contributes to the supply of Q, until with $w = 1$ we reach the unweighted standard summation technology.

Cornes (1993) suggests the geometric mean, $Q = (\prod_{i=1}^{n} q_i)^{1/n}$. This functional form captures the idea that weaker links are significant in the sense that, for a given vector **q**, lower values of q_i imply higher marginal products, since $\dfrac{\partial Q}{\partial q_i} = \dfrac{Q}{n q_i}$. Cornes' analysis shows that the degree of underprovision in the 2-agent weaker link case will depend on the amount of heterogeneity in individuals' incomes or preferences.

In a numerical game theory example, Arce and Sandler (2001) define the public goods' aggregation technology as weaker link if:

$$0 \leq q_j < q_i \Rightarrow \frac{\Delta U}{\Delta q_i} < \frac{\Delta U}{\Delta q_j} \qquad \forall \Delta q_i = \Delta q_j$$

where q_i represents the contribution of individual i and q_j is that of individual j.

This condition specifies that for identical increases in contributions to the public good, the increase to the smallest contribution has the greatest marginal impact on utility. More

recently, Arce (2004) offers the aggregation of $Q = \sqrt{q_i - q_j}$ to describe the underlying weaker link technology.

All of the studies above describe provisions to the weaker link public good under a complete information setting. The present paper extends these studies to examine how provisions to the weaker link public good are affected by the realistic assumption of incomplete information between agents.

IV.   Model

Following Cornes (1993), we define the aggregation technology for the public good as the geometric mean over all contributions. Furthermore, we assume symmetry in benefits from the provision of public good (defined by its total provision), and asymmetric costs of provision. The lowest contributor has the highest marginal effect on the supply of the public good. The aggregation technology describing the total amount of public good provided for the two-region case is defined as:

$$Q(q_1, q_2) = \sqrt{q_1 q_2} \tag{1}$$

To capture the impact of investing in the public good of invasive species prevention, the payoff function consists of a benefit component which expresses the foregone damage

resulting from the total prevention employed, as well as a cost component from executing

and operating the individual prevention measure. Utility for the two-region case can then

be defined as net benefits from provision, or the difference between the total prevention

provided and the cost of the individual region's prevention:

$$U^i(q_i(c_i,c_j),q_j(c_i,c_j)) = Q - c_i q_i(c_i,c_j)^2, \qquad i \neq j$$

This utility function captures the essence of weaker link public goods, as smaller

contributions result in higher marginal benefits than large contributions. Each region

decides simultaneously how much to contribute to the public good of invasive species

prevention. Strategy spaces are defined continuously between $[0.01,\infty)$ so that

$0.01 \leq q_i(c_i) < \infty$. The lower bound of the strategy space prevents regions from falling

into the weakest link problem (whereby if one region contributes zero, utility from the

aggregate public good is zero). This lower bound could represent actions by private

individuals that mitigate introductions of species into new areas[2]. All contributions incur

a per unit contribution cost $0.01 < c_i \leq 1$.

We now move to a more general analysis of the 2-region prevention problem. We begin

by solving for the efficient level of prevention under the weaker link technology, then

compare equilibrium prevention levels under complete and incomplete information to this

benchmark.

V.   Efficient levels of provision under the weaker link technology

Utility and the public good's aggregation technology are defined by the following (dropping cost contingencies for ease of notation):

$$U^i(q_i, q_j, c_i) = Q - c_i q_i^2, \qquad\qquad i \neq j$$

$$Q(q_i, q_j) = \sqrt{q_i q_j}$$

To solve for the Pareto optimal contribution levels under the weaker link technology, the social planner maximizes the utility of one region while holding the other constant by simultaneous choice of q_i, q_j [3].

$$\underset{q_i, q_j}{MAX} \qquad (q_i q_j)^{\frac{1}{2}} - c_i q_i^2 \qquad \text{such that} \quad U^j \geq \overline{U}^j$$

The following condition describes the Pareto optimal prevention for the weaker link case:

Symmetric costs:

$$q_i = \frac{1+\lambda}{4 c_i \lambda^{\frac{1}{4}}}, \qquad q_j = \frac{1+\lambda}{4 c_j \lambda^{\frac{3}{4}}} \tag{2}$$

Asymmetric costs:

$$q_i = \frac{1+\lambda}{(4 c_i)^{\frac{3}{4}} (4\lambda c_j)^{\frac{1}{4}}}, \qquad q_j = \frac{1+\lambda}{(4 c_i)^{\frac{1}{4}} (4\lambda c_j)^{\frac{3}{4}}} \tag{3}$$

VI.   Complete information and the weaker link public good

Will equilibrium prevention levels match the efficient level? Utility and aggregation are

defined as above. If each region knows the other's cost, they can calculate their preferred

quantity based on both their own cost and the other's cost. Under complete information,

each region knows each other's cost of provision.

Region i's problem is therefore[4]:

$$\underset{q_i}{MAX} \quad \sqrt{q_i q_j} - c_i q_i^2$$

The Nash Equilibrium for the weaker link, complete information case is as follows:

Symmetric costs: Asymmetric costs:

$$q_i(c_i)^* = \frac{1}{4c_i}\,, \qquad q_i(c_i)^* = \frac{1}{(4c_i)^{\frac{3}{4}}(4c_j)^{\frac{1}{4}}}\,, \quad q_j(c_j)^* = \frac{1}{(4c_j)^{\frac{3}{4}}(4c_i)^{\frac{1}{4}}} \qquad (4)$$

Compare these to Conditions 2 and 3. Since the Lagrange multiplier $\lambda > 0$, the efficient level of provision will be greater than that provided in the complete information equilibrium. Prevention will be underprovided in equilibrium compared to the efficient level. We will now investigate if incomplete information changes this outcome.

VII.   Incomplete information and the weaker link public good

Information regarding prevention costs is a significant element in the avoidance of invasive species. Different regions of the world will have varying costs for prevention. One example is the heterogeneity of their respective environments. Stylized facts from invasion biology (Simberloff 1995, Lonsdale 1999, Stachowicz et al. 1999) suggest that islands are more easily invaded than continents, as are places with lower biodiversity than are richly diverse regions. This implies that, per unit of prevention, islands and non-diverse areas face higher costs of prevention (*ceteris paribus*), since they are easier to invade. Continents and highly biodiverse areas are equipped with more natural prevention mechanisms, thus face lower per unit prevention costs. While these generalizations have been confirmed in some cases, several studies (Levine and D'Antonio 1999, Sher and Hyatt 1999, Levine 2000) argue that they do not hold in all cases. Further complicating matters is the fact that places like Hawaii are both biodiverse and islands regions, making their "prevention cost" less obvious to their neighbors.

Since the other region's costs are essentially unobservable for these and other (e.g., technological, institutional, political, etc.) reasons, we have a static game of incomplete information. The appropriate solution concept is therefore Bayes Nash Equilibrium. It is assumed that both regions know their own cost but have an incomplete understanding regarding the other's costs. More precisely, costs for each region will be high with probability θ, and low with probability 1-θ, such that $c_L < c_H$. The production function of the public good is again defined by the following weaker link technology:

$$Q(q_i, q_j) = \sqrt{q_i(c_i)q_j(c_j)} \tag{5}$$

Once again, an individual region's utility is defined as the net benefit from provision,

$$U^i(q_i, q_j) = \sqrt{q_i q_j} - c_i q_i^2, \qquad i \neq j \tag{6}$$

We will focus on a symmetric Bayesian Nash Equilibrium (BNE) of the resulting game. The BNE consists of a pair of cost contingent strategies ($q_i^*(\cdot), q_j^*(\cdot)$) such that for each region i and every possible value of c_i, strategy $q_i^*(c_i)$ maximizes

$$E_{q_j} U_i(q_i, q_j^*(c_j), c_i) \qquad (j \neq i)$$

Region i's optimal strategy will give her the highest expected utility given j's optimal strategy. However under incomplete information, each region has only incomplete information regarding the other's cost, so they each have to maximize expected utility, and both regions' optimal contributions will be cost contingent.

If a region's cost is c_i, then for $c_i \in \{c_L, c_H\}$, region i's problem[5] is:

$$\underset{q_i(c_i)}{MAX} \quad \sqrt{q_i(c_i)[\theta q_j(c_H) + (1-\theta)q_j(c_L)]} - c_i q_i(c_i)^2$$

The symmetric BNE is:

$$q^*(c_H) = \frac{1}{4\sqrt{\theta c_H{}^2 + (1-\theta)c_H^{\frac{4}{3}}c_L^{\frac{2}{3}}}}$$

$$q^*(c_L) = \frac{1}{4\sqrt{\theta c_L^{\frac{4}{3}}c_H^{\frac{2}{3}} + (1-\theta)c_L{}^2}}$$

(7)

Comparing Condition 7 to that of 2 and 3, it is clear that in equilibrium under incomplete information, contributions will be below the efficient level (since the Lagrange multiplier $\lambda > 0$). However, it is not clear how these provision levels will compare to the provisions under complete information. In order to draw any conclusions from these conditions, it is necessary to consider the structure of information. That is, whether both regions have high costs (HH), both have low costs (LL), or the regions have an asymmetry of costs (HL or LH).

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VIII. Ex ante comparisons of contribution levels

The main question of interest to policymakers concerns how equilibrium contributions to the prevention public good will compare to the socially optimal level. Our analysis shows that equilibrium prevention, regardless of information structure, will never achieve the Pareto optimal level. However, it is not clear how the structure of information affects the degree of underprovision. To conceptualize the equilibrium comparisons, refer to Table 1 below. This table describes all of the possible type realizations, and their accompanying comparisons.

<Table 1 here>

It would be particularly useful to know, ex ante, how far we can expect to be from the socially optimal level, given the expected difference between complete and incomplete information. To generalize this difference, we construct a deviation function, which describes the ex ante difference in total equilibrium provision levels between the complete and incomplete information states of the world.

The deviation function is constructed as follows:

$$
\begin{aligned}
D(\theta, c_H, c_L) = \quad & \theta^2 \, [Q^{COMPLETE}(c_H, c_H) - Q^{INCOMPLETE}(c_H, c_H)] \\
& + 2\theta(1-\theta)[Q^{COMPLETE}(c_H, c_L) - Q^{INCOMPLETE}(c_H, c_L)] \\
& + (1-\theta)^2 \, [Q^{COMPLETE}(c_L, c_L) - Q^{INCOMPLETE}(c_L, c_L)]
\end{aligned}
\tag{8}
$$

Plugging Equations (4) and (7) into the above deviation function, Equation (8), we arrive at the following general form:

$$D\,(\theta, c_H, c_L) = \quad \theta^2 \left[\frac{1}{2c_H} - \frac{1}{2\sqrt{\theta c_H{}^2 + (1-\theta)c_H{}^{\frac{4}{3}}c_L{}^{\frac{2}{3}}}}\right]$$

$$+\, 2\theta\,(1\text{-}\theta)\left[\left(\frac{1}{(4c_H)^{\frac{3}{4}}(4c_L)^{\frac{1}{4}}} + \frac{1}{(4c_H)^{\frac{1}{4}}(4c_L)^{\frac{3}{4}}}\right) - \right.$$

$$\left. \left(\frac{1}{4\sqrt{\theta c_H{}^2 + (1-\theta)c_H{}^{\frac{4}{3}}c_L{}^{\frac{2}{3}}}} + \frac{1}{4\sqrt{\theta c_L{}^{\frac{4}{3}}c_H{}^{\frac{2}{3}} + (1-\theta)c_L{}^2}}\right)\right]$$

$$+\, (1\text{-}\theta)^2 \left[\frac{1}{2c_L} - \frac{1}{2\sqrt{\theta c_L{}^{\frac{4}{3}}c_H{}^{\frac{2}{3}} + (1-\theta)c_L{}^2}}\right]$$

$$\tag{9}$$

Equation (9) describes the ex ante difference we can expect between equilibrium contributions provided under complete and incomplete information. Its sign will reveal whether we can expect more to be provided under complete information (if positive) or under incomplete information (if negative). Graphing the deviation function in three-dimensional space[6], we observe that the value of this function will always be positive given any range of θ, c_H, and c_L. These results suggest that ex ante, more will be provided under the complete information regime. While prevention is underprovided under complete information, incompleteness of information leads to an even more severe underprovision of prevention.

It is also interesting to see how the expected difference in prevention levels changes as a function of θ, c_H, and c_L. We take the respective partial derivatives (suppressing results due to complexity of equations), and then interpret these using the curvatures in Panels 1 − 3 in Appendix D. From Panel 1, the curvature of the deviation function reveals

$\frac{\partial D}{\partial c_H} > 0$. Holding c_L constant and increasing c_H (in other words, spreading the costs farther apart) increases the deviation. Panel 2 shows the opposite to be true, $\frac{\partial D}{\partial c_L} < 0$. Holding c_H constant and increasing c_L (bringing the costs closer together) decreases the deviation between provision levels. Together, the costs comparative statics show that when costs are closer together we see increased efficiency, due to the lower expected deviation between provision levels.

These two results hold unambiguously. Theta's comparative static, however, depends on the magnitude of θ. For lower levels of θ, $\frac{\partial D}{\partial \theta} > 0$. Low θ means a region is more likely to be a low cost provider of prevention. But as θ increases, so will the deviation between provision levels. This result is consistent with the costs comparative statics above. The expected deviation in provision levels is larger if costs are expected to be farther apart. Similarly, for higher θ, $\frac{\partial D}{\partial \theta} < 0$. If costs are expected to be high, increasing theta reduces expected deviation between provision levels.

It is not immediately obvious whether it is simply the absolute values of the costs c_L and c_H driving these results, or whether the difference between the two cost levels also plays a role in determining how far apart provision levels in the two states of the world are expected to be. To investigate, we again plot the deviation function in three-dimensional space, but this time with the difference between the cost levels as the third dimension.

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We see from Figure 1 that indeed the value of the low cost region, as well as the difference between the two cost levels, affects the deviation in provision levels. We can compare the value that the deviation function takes on for a given theta, for example $\theta = 0.5$. When c_L is low, $D \approx 0.6$. When c_L is high, D is much smaller, around 0.0003.

<Figure 1 here>

From Figure 1 we can say the following. The deviation between provision levels in the two states of the world will be larger for low cost regions. This deviation grows smaller as cost increases. This may be because high-cost regions are constrained by their own costs, so the incompleteness of information does not lead to as large an expected difference as with lower cost regions. This is the case even when the actual cost difference between the two regions is the same. For example, the deviation given $c_L = 0.8$ and $c_H = 0.9$ will be less than the deviation given $c_L = 0.1$ and $c_H = 0.2$. Thus, incompleteness of information is more inefficient when the regions have lower prevention costs. This is illustrated in Figure 2 below in the two-dimensional graph of deviation as a function of the difference between c_L and c_H.

< Figure 2 here>

The top curve in Figure 2 represents the value of the deviation function when c_L starts at

0.1. The lower two curves represent the value of the deviation function when c_L starts at

0.5 and 0.9, respectively. As evident from the picture, the deviation in provision levels

depends not only on the magnitudes of the costs, but how far apart they are from one

another.

IX.   Ex Post Comparisons

The following section investigates how equilibrium provisions compare under complete

and incomplete information *ex post*, that is, after costs have been realized. Case- by-case

comparisons are drawn for potential insights.

We first compare the case in which the regions' costs are at either extreme, c_H=1,

c_L=0.01. We begin with the ex ante probability of a region being a high cost provider as

$\theta = 0.1$. Single prevention levels are reported and compared, as regions are completely

symmetric in the model. Table 2 below reports results.

<Table 2 here>

As observed in the table, incomplete information *ex post* no longer implies inefficiency.

Rather, it appears that this information structure may help or hinder efficiency. We obtain

similar results when $\theta = 0.9$ and $\theta = 0.5$. A couple cases are worth mentioning. If both

regions are high cost (HH), more is always provided in the incomplete information case.

Ceteris parabis, high cost regions are able to provide less than low cost regions. High cost regions that know the other is also high cost will thus provide more under incomplete information. There exist other cases for which equilibrium contributions will be higher under incomplete information. For example, if the cost structure is LH (I am low cost, you are high cost), but $\theta = 0.1$ so I believe you are low cost, I will provide more under this (incorrect) belief than if I knew your true cost (high).

The key to interpreting these results is to recall that the region with the smallest prevention will have the largest marginal benefit. For the region doing more prevention, there is less gain from additional contributions, so there is an incentive to provide less than the other region in equilibrium. However, higher joint contributions mean higher utility. Therefore, each region will, in equilibrium, try to be the weaker link (lower level provider), so that future contributions are marginally more beneficial.

As we mention in the opening of Section VIII, equilibrium prevention, regardless of information or cost structure, will never reach the Pareto optimal level. The following figure illustrates that although equilibrium prevention will depend on the region's belief of the other's cost structure, as well as the actual cost structure itself, prevention of invasive species will always be underprovided in equilibrium.

<Figure 3 here>

Figure 3 shows how prevention levels will vary depending on probability θ. Contributions levels are higher for low cost regions, and when regions are believed to be low cost ($\theta=0.1$), contributions are highest. When regions are believed to be high cost ($\theta=0.9$), contribution levels are lowest. Provision levels fall in between these two extremes when regions believe there is an equal chance the other is high or low ($\theta=0.5$).

<Figure 4 here>

Figure 4 displays equilibrium contributions as a function of cost for the symmetric (HH or LL) case, given equal probabilities of high or low cost types being realized. Although hard to see in the graph, slightly more will always be provided under complete information, the difference in the two provision levels decreasing with increasing cost. At the maximum cost level, provision will be the same. Again, the efficient level will not be reached under either information assumption.

X.   Implications

Contributions to the transnational, weaker link public good of invasive species prevention have been shown to suffer from underprovision. Regions underinvest in prevention compared to the efficient level. This phenomenon can be explained by the weaker link technology that aggregates contributions to this type of public good. Lower contribution levels result in higher marginal benefits for the smaller provider. Thus, each region has an incentive to provide less prevention than their neighbor.

The structure of cost information between the regions also appears to have an effect on equilibrium levels of prevention. Ex ante, before costs are realized, incompleteness of information has been shown to lead to inefficiently lower levels of prevention than in the complete information case. Ex post, however, we find that incomplete information may lead to higher prevention levels. In particular, when a low cost region falsely believes their neighbor is also low cost, they will overinvest as compared to the complete information case, leading to a more efficient outcome.

Because policymakers make decisions from an ex ante perspective, completeness of information is the preferred objective. This implies that more transparent costs will result in more efficient provision levels. Movement towards greater transparency is evident in the formation of networks such as GISP (Global Invasive Species Program), NISC (National Invasive Species Council), NBII (National Biological Information Infrastructure), and ISSG (Invasive Species Specialist Group), amongst others. These organizations have formed global networks to share prevention strategies and provide detailed information regarding mitigation programs.

Comparative statics analysis of the deviation function shows that when regions' prevention costs are more similar, a more efficient prevention outcome is reached. This suggests that Pareto-improving transfers from low cost to high cost regions may be advantageous. Another important possibility that remains includes extending the model to repeated play. We may be able to get Pareto optimal levels of provisions given more than

one round of decision-making, particularly under the complete information regime. Also, it would be useful to allow for multiple players, since there are many more than two regions involved in this type of decision-making.

This paper was a first step towards investigating how the weaker link technology affects equilibrium prevention of invasive species under incomplete information. While the focus was on the nature of the public good itself, a more complete model of this type of decision making would need to include the type of prevention activity being employed, the income and preferences of the regions, and the probability of invasion. This prospect is left for future work.

Appendix A. Efficient levels of provision under the weaker link technology

The social planner's problem is:

$$\underset{q_i, q_j}{MAX} \quad (q_i q_j)^{\frac{1}{2}} - c_i q_i^2 \qquad \text{such that} \quad U^j \geq \overline{U}^j$$

$$L = (q_i q_j)^{\frac{1}{2}} - c_i q_i^2 + \lambda[(q_i q_j)^{\frac{1}{2}} - c_j q_j^2 - \overline{U}^j]$$

$$\frac{\partial L}{\partial q_i} = \frac{1}{2}(q_i q_j)^{\frac{-1}{2}} q_j - 2 c_i q_i + \frac{1}{2}\lambda(q_i q_j)^{\frac{-1}{2}} q_j = 0 \tag{A1}$$

$$\frac{\partial L}{\partial q_j} = \frac{1}{2}(q_i q_j)^{\frac{-1}{2}} q_i + \frac{1}{2}\lambda(q_i q_j)^{\frac{-1}{2}} q_i - 2\lambda c_j q_j = 0 \tag{A2}$$

$$\frac{\partial L}{\partial \lambda} = (q_i q_j)^{\frac{1}{2}} - c_j q_j^2 = \overline{U}^j$$

Rearranging Equations A1 and A2 and plugging one into the other,

$$q_i = \frac{(1+\lambda)}{(4 c_i)^{\frac{3}{4}}(4\lambda c_j)^{\frac{1}{4}}} \tag{A3}$$

$$q_j = \frac{(1+\lambda)}{(4 c_i)^{\frac{1}{4}}(4\lambda c_j)^{\frac{3}{4}}} \tag{A4}$$

Therefore, the following condition describes the Pareto optimal provisions for the weaker link case:

Symmetric costs:

$$q_i = \frac{1+\lambda}{4c_i\lambda^{\frac{1}{4}}}, \qquad q_j = \frac{1+\lambda}{4c_j\lambda^{\frac{3}{4}}} \qquad\qquad\qquad (A5)$$

Asymmetric costs:

$$q_i = \frac{1+\lambda}{(4c_i)^{\frac{3}{4}}(4\lambda c_j)^{\frac{1}{4}}}, \qquad q_j = \frac{1+\lambda}{(4c_i)^{\frac{1}{4}}(4\lambda c_j)^{\frac{3}{4}}} \qquad\qquad\qquad (A6)$$

Appendix B. Complete information and the weaker link public good

Region i's problem:

$$\underset{q_i}{MAX} \quad \sqrt{q_i q_j} - c_i q_i^2$$

$$L = \sqrt{q_i q_j} - c_i q_i^2$$

$$\frac{\partial L}{\partial q_i} = \frac{1}{2}[q_i q_j]^{-\frac{1}{2}} q_j - 2c_i q_i = 0$$

$$q_i = \frac{q_j^{\frac{1}{3}}}{(4c_i)^{\frac{2}{3}}} \qquad\qquad\qquad (B1)$$

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By symmetry,

$$q_j = \frac{q_i^{\frac{1}{3}}}{(4c_j)^{\frac{2}{3}}} \tag{B2}$$

Solving for the Nash Equilibrium, plugging B2 into B1,

$$q_i^* = \frac{1}{(4c_i)^{\frac{3}{4}}(4c_j)^{\frac{1}{4}}} \tag{B3}$$

The Nash Equilibrium for the weaker link, complete information case is thus:

Symmetric costs: Asymmetric costs:

$$q_i(c_i)^* = \frac{1}{4c_i}, \qquad q_i(c_H)^* = \frac{1}{(4c_H)^{\frac{3}{4}}(4c_L)^{\frac{1}{4}}}, \quad q_j(c_L)^* = \frac{1}{(4c_L)^{\frac{3}{4}}(4c_H)^{\frac{1}{4}}} \tag{B4}$$

Appendix C. Incomplete information and the weaker link public good

$$L = \sqrt{q_i(c_H)[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)]} - c_H\, q_i(c_H)^2$$

$$\frac{\partial L}{\partial q_i(c_H)} = \frac{1}{2}[q_i(c_H)[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)]]^{-\frac{1}{2}}[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)] - 2c_H\, q_i(c_H) = 0$$

$$q_i(c_H) = \frac{[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)]^{\frac{1}{3}}}{(4c_H)^{\frac{2}{3}}}$$

Each region's reaction function will depend on their own realization of costs:

$$q_i(c_H) = \frac{[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)]^{\frac{1}{3}}}{(4c_H)^{\frac{2}{3}}}$$

$$q_i(c_L) = \frac{[\theta\, q_j(c_H) + (1-\theta)q_j(c_L)]^{\frac{1}{3}}}{(4c_L)^{\frac{2}{3}}}$$

(C1)

In a symmetric Bayesian Nash Equilibrium,

$$q_i(c_H) = q_j(c_H) = q^*(c_H)$$
$$q_i(c_L) = q_j(c_L) = q^*(c_L)$$

Therefore,

$$q^*(c_H) = \frac{[\theta q^*(c_H) + (1-\theta) q^*(c_L)]^{\frac{1}{3}}}{(4c_H)^{\frac{2}{3}}}$$

$$q^*(c_L) = \frac{[\theta q^*(c_H) + (1-\theta) q^*(c_L)]^{\frac{1}{3}}}{(4c_L)^{\frac{2}{3}}}$$

(C2)

To solve for the Bayesian Nash Equilibrium,

Let x = $q^*(c_H)$

  y = $q^*(c_L)$

Then,

$$x = \frac{[\theta x + (1-\theta)y]^{\frac{1}{3}}}{(4c_H)^{\frac{2}{3}}}$$

(C3)

$$y = \frac{[\theta x + (1-\theta)y]^{\frac{1}{3}}}{(4c_L)^{\frac{2}{3}}}$$

(C4)

After rearranging and manipulating Equations C3 and C4, the resulting symmetric BNE

is therefore:

$$q^*(c_H) = \frac{1}{4\sqrt{\theta c_H{}^2 + (1-\theta) c_H^{\frac{4}{3}} c_L^{\frac{2}{3}}}}$$

$$q^*(c_L) = \frac{1}{4\sqrt{\theta c_L^{\frac{4}{3}} c_H^{\frac{2}{3}} + (1-\theta) c_L{}^2}}$$

Appendix D. The deviation function in 3-dimensional space

In panel 1, we hold c_L at a constant value and vary c_H accordingly. Panel 2 does the same for c_H, varying c_L accordingly. Panel 3 illustrates the deviation function for given values of θ, while varying both cost levels.

Panel 1.

cL = 0.1, θ ∈ [0,1], cH ∈ [0.1,1]

cL = 0.5, θ ∈ [0,1], cH ∈ [0.5,1]

cL = 0.9, θ ∈ [0,1], cH ∈ [0.9,1]

Panel 2.

cH = 0.9, θ ∈ [0,1], cL ∈ [0.01,0.9]

cH = 0.5, θ ∈ [0,1], cL ∈ [0.01,0.5]

cH = 0.1, θ ∈ [0,1], cL ∈ [0.01,0.1]

Panel 3. For all graphs, cL ∈ [0.01,1], cH ∈ [0.01,1]

θ = 0.1

θ = 0.5

θ = 0.9

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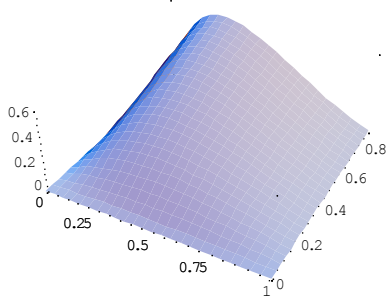
Table 1. Ex ante total contribution comparisons for all possible type realizations

Cost structure	With probability	**COMPLETE**		**INCOMPLETE**
HH	θ^2	$Q^{COMP}(c_H, c_H)$	$<, =, >$	$Q^{INCOMP}(c_H, c_H)$
HL	$\theta(1-\theta)$	$Q^{COMP}(c_H, c_L)$	$<, =, >$	$Q^{INCOMP}(c_H, c_L)$
LH	$(1-\theta)\theta$	$Q^{COMP}(c_L, c_H)$	$<, =, >$	$Q^{INCOMP}(c_L, c_H)$
LL	$(1-\theta)^2$	$Q^{COMP}(c_L, c_L)$	$<, =, >$	$Q^{INCOMP}(c_L, c_L)$

Table 2. Ex post single region prevention comparisons: c_H=1, c_L=0.01, $\theta = 0.1$

Cost structure	With probability ($\theta = 0.1$)	**COMPLETE**	<, =, >	**INCOMPLETE**
HH	$è^2$	0.003	<	0.007
HL	$\theta(1-\theta)$	0.07	>	0.06
LH	$(1-\theta)\theta$	0.71	<	1.22
LL	$(1-è)^2$	20.25	>	10.96

Figure 1. Deviation function as a function of theta and $c_H - c_L$, 3-dimensional

cL = 0.1   cL = 0.5

cL = 0.9

Figure 2. Deviation as a function of $c_H - c_L$
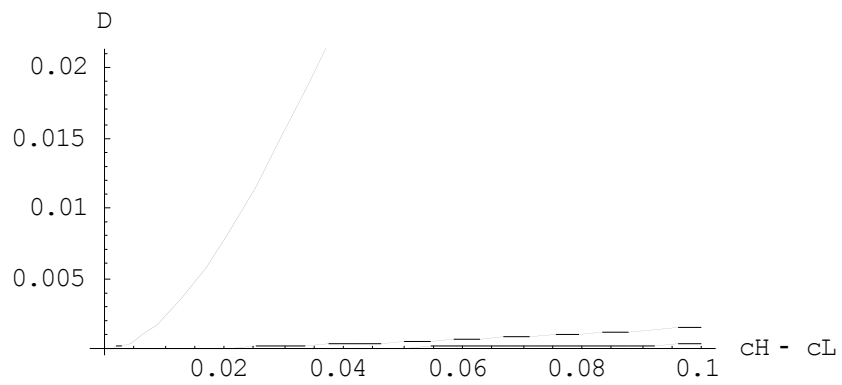
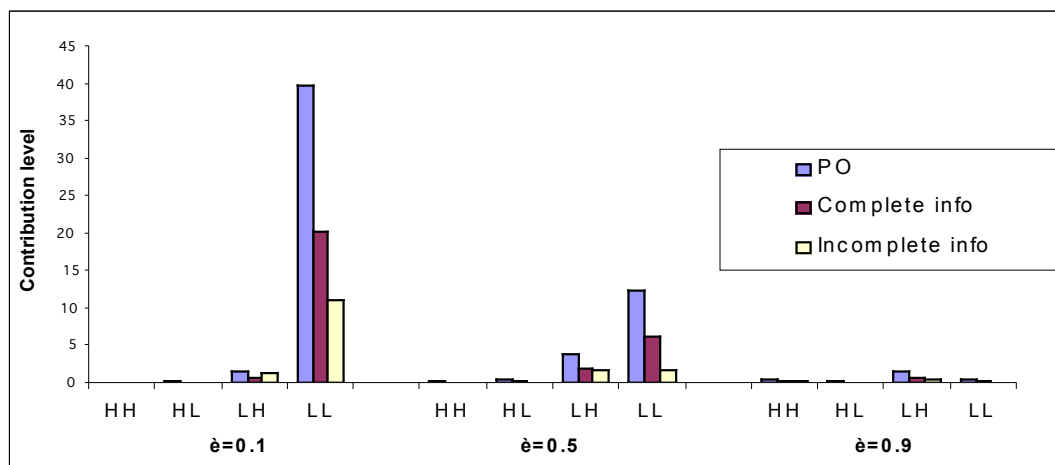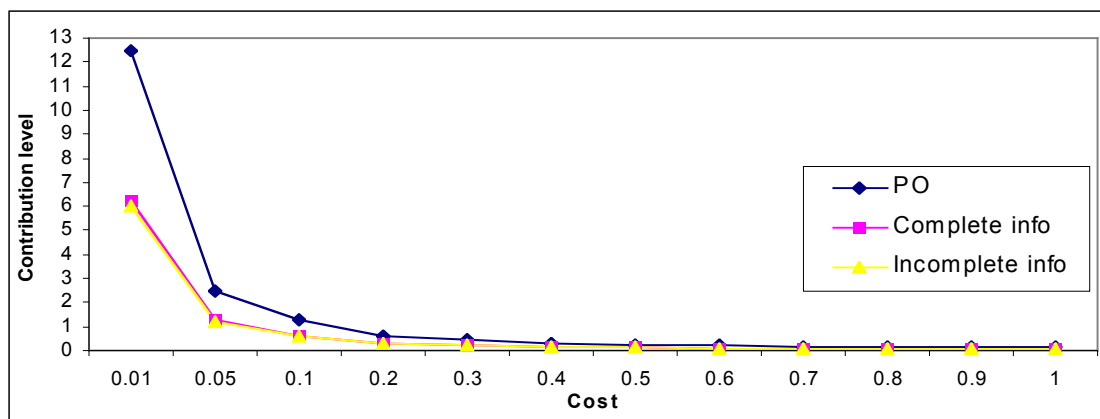Figure 3. Efficient vs. equilibrium prevention[7] for varying θ

Figure 4. Contributions as a function of cost, symmetric, θ=0.5.

Endnotes

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[1] Most of the problems that have been associated with invasive species were instigated by accidental or unintentional introductions of nonindigenous species, including zebra mussels, termites, fire ants, and many other examples. The other category of invasive specie are those which are intentionally or deliberately introduced to an area, in hopes of gaining some positive level of benefit from the introduction. This type of introduction differs fundamentally from that of the unintentional introduction, in that the probability of arrival is equal to 1.

2 For example, private citizens in Hawaii have prevented snake establishments by

sighting and killing snakes on their own accord.

3 See Appendix A for full derivation

4 See Appendix B for full derivation

5 See Appendix C for full derivation.

6 See Appendix D for graphical analysis

7 This analysis assumes $c_H=1$ and $c_L=0.01$. Similar but less dramatic results are obtained

when costs are closer together.