Introductions of Invasive Species: Failure of the Weaker Link

Kimberly M. Burnett

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 provide benefits, but these benefits progressively decline as contributions exceed the minimum. A two-region model is constructed, assuming incomplete information concerning costs of provision. This framework allows us to explain why we observe underinvestment in prevention, how information facilitates efficiency, and under what conditions information is most relevant. Specific implications regarding improved invasive species prevention policy are extracted and discussed.

Key Words: weaker link, invasive species, public good aggregation

The prevention of biological invasions can be described as an impure public good due to its substantial degree of nonrival benefits and nonexcludable beneficiaries. Failure to halt an invasion at one border puts other regions[1] at risk, particularly if the regions share a border or engage in heavy trade. For example, the state of Hawaii benefits from other states' diligence in the control and treatment of mosquitoes, potential vectors for the West Nile virus. To date, Hawaii is one of only two states in the United States free of this virus, largely due to California-based efforts to control its own mosquito population. California cannot exclude Hawaii from reaping these external benefits.

However, prevention of unwanted organisms is a special type of public good. Regardless of a particular region's technological sophistication in thwarting invasion, if other regions have few or no measures in place, the diligent region's efforts to keep invasives out will be less efficacious. This may have important implications for individual investments in invasive species prevention, as high levels of expenditures in a given region do not necessarily imply high levels of effective prevention. Each area's ability to prevent invasions is largely determined by the regions with the weakest prevention technologies.

Several authors (Conybeare, Murdoch, and Sandler 1994, Vicary and Sandler 2002, Perrings et al. 2002) have characterized the prevention of invasions as a "weakest link" public good. That is, the overall level of prevention in the world is determined by the weakest contributor, or the region that does the least amount of 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. Under the weaker link public good technology, lower investments by others diminish returns to those who invest more, but those who invest more may still enjoy higher protection than those who invest less.

The specific question we address in this work concerns the level of prevention that regions will contribute given the nature of the "weaker link" public good. Our interest lies in how equilibrium

Kimberly Burnett is a graduate student in the Department of Economics at the University of Hawaii at Manoa.

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[1] Regions can be thought of as cities, states, provinces, countries, continents, or any collection of these. Scale does not change the results of the model.

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contribution levels will compare to the socially optimal level under two distinct information structures: the complete information regime, where regions know both their own cost of prevention and the cost their neighbor faces, and the incomplete information regime, under which each region is certain of only its own cost of prevention.

Information regarding prevention costs is a significant determinant of the effectiveness of invasive species avoidance. Different regions of the world will face varying costs of prevention. One reason for this variation is the heterogeneity of their respective environments. Stylized facts from invasion biology (Simberloff 1995, Lonsdale 1999, Stachowicz, Whitlatch, and Osman 1999) suggest that islands are more easily invaded than continents, as are places with lower biodiversity. This implies that, per unit of prevention, islands and less 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, and thus face lower per unit prevention costs. While these characterizations 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 general. Further complicating matters is the fact that some island chains such as Hawaii are rich in biodiversity, making their "prevention cost" less obvious to their neighbors.

This analysis builds upon existing literature in two ways. First, we frame the invasive species problem in a public goods context and are thus able to explain why we observe inadequate prevention and high levels of invasion around the world. Second, we extend the public goods literature by modeling the weaker link aggregation technology under an incomplete information regime. Using this framework, we are able to extract specific implications regarding improved invasive species prevention policy.

Relevant literature is reviewed in the following section. We then introduce the two-region model. The efficient level of prevention under the weaker link aggregation technology is developed as the benchmark case, followed by a characterization and comparison of equilibrium prevention levels under the two information regimes and a discussion of comparative statics. The final section presents policy implications and concludes.

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 individual contributions to that good (e.g., Chamberlin 1974, Cornes and Sandler 1984, Bergstrom, Blume, and Varian 1986). Hirshleifer (1983, 1985) extends the analysis of public goods to include models that do not fall into this class of production functions. He identifies three distinct public good technologies. First, the ordinary "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. Hirshleifer then distinguishes two extreme cases, the weakest link model,

$$Q = \min_i q_i \,,$$

and the best-shot model,

$$Q = \max_i q_i \,.$$

In the weakest link case, the total quantity available to each agent equals the smallest individual contribution, and in the best-shot case, 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. Hirshleifer (1984) then extends his definition to include another form of social composition functions, a more general case involving weights w_i, in which

$$Q = \sum_i w_i \, q_i \,,$$

where $w_i = 1$ for the smallest q_i, and $0 < w_j < 1$ 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 link technology used here.

Cornes (1993) uses the geometric mean,

$$Q = (\prod_{i=1}^{n} q_i)^{1/n},$$

to describe the weaker link public good. This functional form captures the idea that weaker links are important in the sense that, for a given vector **q**, smaller values of q_i imply larger marginal products, since $\partial Q/\partial q_i = Q/nq_i$. Cornes' analysis shows that the degree of underprovision in the two-agent weaker link case will depend on the amount of heterogeneity in individuals' preferences and incomes. Agents' incomes are compared with the minimum cost of attaining the efficient outcome. While some Pareto-improving income transfers are identified, as income distribution becomes more unequal, the inefficiency grows. We extend this analysis by comparing equilibrium and Pareto optimal outcomes in a game theoretic setting.

Model

Following Cornes (1993), we define the aggregation technology for the prevention public good as the geometric mean over all contributions. We assume symmetry in benefits from the provision of the 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 describe the utility from investing in the public good of invasive species prevention, the payoff function consists of a benefit component representing avoided damages, as well as a cost component from executing and operating the prevention measure. Individual utility 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:

$$U^i(q_i, q_j) = Q - c_i q_i^2\,. \tag{2}$$

This simple utility function captures the essence of weaker link public goods, as the player making the smaller contribution will enjoy higher marginal benefits than the player contributing more. This is a direct result of the specification of the production function.

The game proceeds as follows. Each region decides simultaneously how much to contribute to the public good of invasive species prevention. Strategy spaces are defined continuously between $(0, \infty)$ so that $0 < q_i(c_i) < \infty$,[2] and all contributions incur a quadratic contribution cost, with $0 < c_i \leq 1$.

Below we solve for the efficient level of prevention under the weaker link technology, followed by a comparison of the complete and incomplete information equilibrium prevention levels to this benchmark.

Efficient Prevention

Equations (1) and (2) above define the production function and individual utility to be used throughout the paper. To solve for the Pareto optimal contribution levels, the social planner maximizes the utility of one region while holding the other constant[3] by simultaneous choice of q_i and q_j:

$$\max_{q_i, q_j} \; (q_i q_j)^{1/2} - c_i q_i^2 \;\; \text{such that} \;\; U^j \geq \bar{U}^j\,.$$

The following conditions describe the Pareto optimal contributions:

symmetric costs

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

[2] Strategies should be greater than zero, or we are back to the "weakest link" case, whereby if one player contributes zero to the public good, the total benefit, regardless of how much others contributed, falls to zero.

[3] Since we use concave utility functions, this approach of maximizing utility of one player subject to meeting a required utility level of the other is equivalent to maximizing the weighted sum of the utilities of the two players [see Varian (1992, p. 225) and Mas-Colell, Whinston, and Green (1995, p. 328)].

asymmetric costs

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

where λ is the Lagrange multiplier, which can be interpreted as the weight that the social planner places on region *i*'s utility.[4]

Equilibrium Prevention

Complete Information Equilibrium

Will equilibrium prevention levels match the efficient level? Under a setting of complete information, regions can calculate their preferred quantities based on their own cost and the other's cost. Region *i*'s problem is therefore

$$\max_{q_i} \sqrt{q_i q_j} - c_i q_i^2 .$$

The Nash Equilibrium for the complete information case is

$$(5)\qquad q_i(c_i)^* = \frac{1}{(4c_i)^{3/4}(4c_j)^{1/4}} .$$

Compare this condition to equations (3) and (4). Since the Lagrange multiplier λ is greater than zero, the efficient level of provision will be greater than that provided in the complete information equilibrium. Individual regions observe both sets of costs and respond according to their own optimal contribution level, thus ignoring the effect of their decision on the other's utility. We now investigate the equilibrium solution under incomplete information.

Incomplete Information Equilibrium

Since the other region's prevention costs are essentially unobservable for the ecological reasons stated in the introduction, as well as other (e.g., technological, institutional, political) reasons, investment in the prevention of invasive species is generally done in a setting of incomplete information. The appropriate solution concept is therefore the Bayes Nash Equilibrium. The distribution of costs is common knowledge. To simplify our analysis, we assume that costs of prevention are either high (c_H) or low (c_L). More precisely, costs for each region will be high with probability θ, and low with probability $1-\theta$, with $c_L < c_H$.

We 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

$$(6)\qquad E_{q_j}[U_i(q_i, q_j^*(c_j), c_i)] .$$

Region *i*'s optimal strategy will give the highest possible expected utility given *j*'s optimal strategy. 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 is

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

The symmetric BNE is

$$(7)\qquad q^*(c_H) = \frac{1}{4\sqrt{\theta c_H^{\,2} + (1-\theta) c_H^{4/3} c_L^{2/3}}}$$

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

Comparing equation (7) to equations (3) and (4), it is clear that the incomplete information equilibrium will also be below the efficient level (since the Lagrange multiplier λ is greater than zero). We now compare this equilibrium to the complete information equilibrium.

Equilibrium Comparison

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. In what follows we investigate how the structure

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[4] Note that when $\lambda = 1$ and costs are symmetric, the contributions are the same.

of information affects the degree of underprovision.

In order to compare contributions to the public good of invasive species prevention under the two information structures, we first note that the utility-maximizing contribution levels [from equations (5) and (7)] are convex in costs. By convexity, the utility-maximizing quantity associated with the expected value of the other region's cost is *less than* the quantities associated with known costs multiplied by their probabilities.[5] That is, for all i = L, H,

$$\text{(8)}\quad \theta q_i^{COMPLETE}(c_i;c_H)+(1-\theta)q_i^{COMPLETE}(c_i;c_L)\geq q_i^{INCOMPLETE}(c_i).$$

Therefore, for all cost realizations, equilibrium contributions made under incomplete information will be less than those made under complete information.

From equation (5), expected ex ante contributions of q_i are

$$\text{(9)}\quad E(q_i;\theta)=\frac{\theta}{(4c_i)^{3/4}(4c_H)^{1/4}}+\frac{1-\theta}{(4c_i)^{3/4}(4c_L)^{1/4}}.$$

Expected contributions under the Bayes Nash Equilibrium are given in equation (7). Comparing the two expected contribution levels,

$$\text{(10)}\quad \frac{\theta}{(4c_i)^{3/4}(4c_H)^{1/4}}+\frac{1-\theta}{(4c_i)^{3/4}(4c_L)^{1/4}}\geq \frac{1}{4\sqrt{\theta c_H{}^2+(1-\theta)c_H{}^{4/3}c_L{}^{2/3}}}$$

and

$$\text{(11)}\quad \frac{\theta}{(4c_i)^{3/4}(4c_H)^{1/4}}+\frac{1-\theta}{(4c_i)^{3/4}(4c_L)^{1/4}}\geq \frac{1}{4\sqrt{\theta c_L{}^{4/3}c_H{}^{2/3}+(1-\theta)c_L{}^2}},$$

which, by observation, holds for all possible values of θ and c_i.

Comparative Statics

Another way to show that contributions made under incomplete information will always be less than those made under complete information is to construct a deviation function describing the expected difference in total equilibrium prevention levels between the two states of the world:

(12)

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

Equation (12) describes the ex ante difference in equilibrium prevention levels provided under complete and incomplete information. Its sign will reveal whether we can expect more to be provided under complete information (positive) or under incomplete information (negative). We generate a computational solution and graph the deviation function in three-dimensional space.[6] From the graphs we observe that the value of this function will be positive for any θ, c_H, and c_L.

It is also instructive 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 the appendix. From Panel 1, the curvature of the deviation function reveals that $\partial D/\partial c_H>0$. 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, $\partial D/\partial c_L<0$. Holding c_H constant and increasing c_L (bringing the costs closer together) decreases the deviation

[5] A property of convexity—see, e.g., Mas-Colell, Whinston, and Green (1995, p. 931). The author is grateful to an anonymous referee for pointing this out.

[6] See the appendix for graphical analysis. All graphs were created using Mathematica (version 5.0).

between provision levels. These results are driven by the concavity of the net benefit function and the convexity of the quantity function. Together, the cost comparative statics show that when costs are closer together we see increased efficiency, due to the lower expected deviation between contributions.

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

Implications

We now review the three main results of the paper and discuss their relevance for policy.

First, regions will not adequately invest in invasive species prevention. This phenomenon is a direct result of the incentive structure implied by the weaker link public good technology. Individual regions restrict investment in hopes that sufficient prevention will be provided by others. Some degree of outside facilitation is thus warranted.

Second, better information about the prevention costs faced by other regions can generate more efficient total contributions to the public good. When another area's cost of prevention is unknown, less prevention will be provided in equilibrium. This implies that increased transparency in cost reporting may result in more efficient prevention levels. Movement towards greater transparency is evident in the formation of global networks such as the Global Invasive Species Program (GISP), and regional associations such as the National Invasive Species Council (NISC), the National Biological Information Infrastructure (NBII), and the Invasive Species Specialist Group (ISSG).

Finally, we find that when prevention costs are more similar, a more efficient amount of prevention is provided. This suggests that Pareto-improving transfers from low-cost to high-cost regions may be justified. Transparency of costs will also matter more when regions face very different prevention costs. Gains realized from discovering another's prevention costs are higher the more different their cost is from your own. Global networks for invasive species management may then be particularly important, since regional networks share information between locales in which costs are likely to be more similar.

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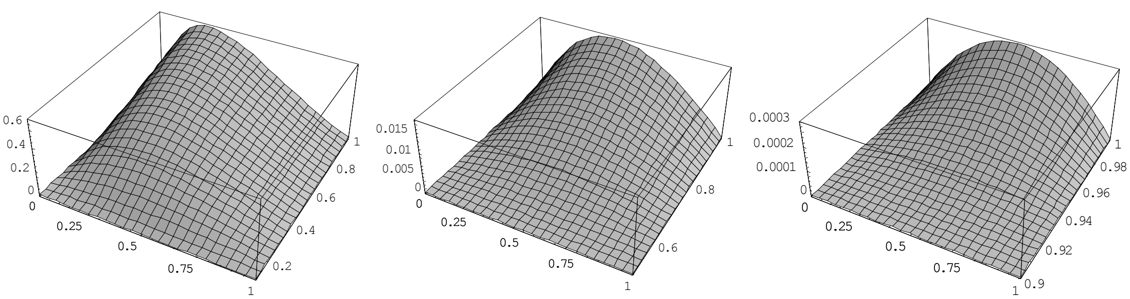
APPENDIX: The Deviation Function in 3-Dimensional Space

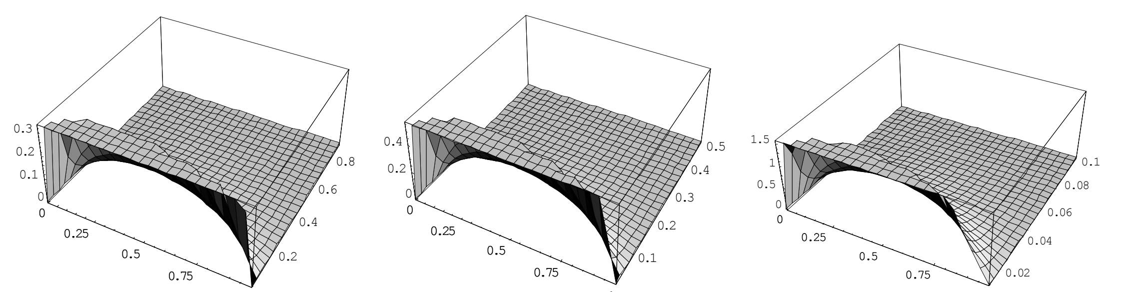
In Panel 1, we hold c_L at a constant value and vary c_H accordingly. Panel 2 does the same for c_H, varying c_L accordingly. Panel 3 illustrates the deviation function for given values of θ, while varying both cost levels.

Panel 1.



$c_L = 0.1$, $\theta \in [0,1]$, $c_H \in [0.1,1]$ $c_L = 0.5$, $\theta \in [0,1]$, $c_H \in [0.5,1]$ $c_L = 0.9$, $\theta \in [0,1]$, $c_H \in [0.9,1]$

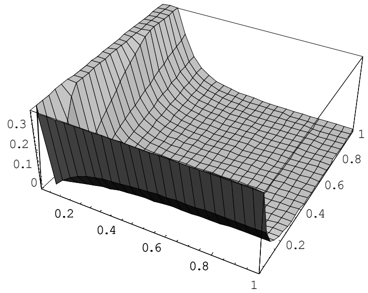
Panel 2.



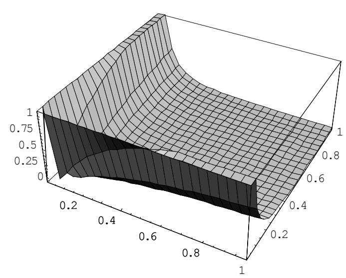
$c_H = 0.9$, $\theta \in [0,1]$, $c_L \in [0.01,0.9]$ $c_H = 0.5$, $\theta \in [0,1]$, $c_L \in [0.01,0.5]$ $c_H = 0.1$, $\theta \in [0,1]$, $c_L \in [0.01,0.1]$

Panel 3.

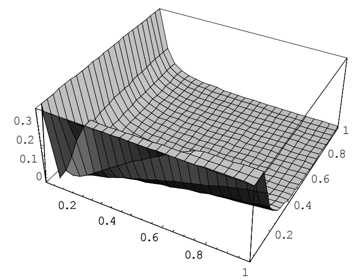
For all graphs, $c_L \in [0.01,1]$, $c_H \in [0.01,1]$.



θ = 0.1



θ = 0.5



θ = 0.9