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ANALYSIS

Least-cost tradeable risk permit scheme for controlling risk of introducing invasive alien species by shipping[☆]

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ABSTRACT

The probability of alien species invasion is reasonably characterized by a weakest link technology. A tradeable risk permit system for shippers has been proposed as a means of efficiently reducing this invasion probability. Economic jointness arising from statistical independence among private risks for the weakest link technology implies that the risk instrument to be traded should be linear in the log of firm success probabilities, rather than linear in firm success probabilities.

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1. Introduction

Alien species have undoubtedly caused great ecological and economic harm, even if costs are difficult to estimate (Pimentel et al., 2000; Pimentel et al., 2005; Hoagland and Jin, 2006; Kalogirou et al., 2007). International trade has been identified as an important factor in the introduction of alien species (Westphal et al., 2008). A variety of policy prescriptions have been proposed, including ambient taxes (Jones and Corona, 2008) and biosecurity effort subsidies (Horan and Lupi, 2005a).

A case of particular interest has been the role of commercial shipping as a transport medium for invasion of the North American Great Lakes. A very interesting and relevant analysis was provided in Horan and Lupi (2005b), who model the use of a risk trading permit scheme for shippers. In it, shipping firms take risk abatement actions and have the risk they present measured by a regulator. The regulator also imposes a certain overall risk constraint, and shipping firms trade permits for assessed risk such that the overall risk constraint is satisfied. Risks are independent and their risk constraint is linear in firm success probabilities.

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Relative to a linear risk constraint, herein we show that further cost efficiency gains can be obtained from exploiting linearity of the log of the overall success probability in the log of firm success probabilities. Then permits can be traded on a one-for-one basis such that, importantly, the aggregate likelihood of an invasion is preserved at a given level. One-for-one trading is important in that it avoids the need for assessing transfer coefficients, and so reduces the extent of transactions costs. In turn such costs can reduce trade liquidity, even to the point where the market is not viable.

2. Algebra of invasion constraint

The set of shipping firms is denoted by $i \in \{1, \dots, n\} = \Omega_n$, and each firm travels the same route just once (round trip) per year. The probability that the i th firm is responsible, at least in part, for an alien species invasion is specified as q_i so that the probability of that firm's success in not being responsible for an invasion is $\bar{q}_i = 1 - q_i$. We refer to q_i and $\bar{q}_i$ as, respectively, the individual failure and success probabilities. Under risk independence, the overall probability of an invasion is

$$P(\bar{q}_1, \dots, \bar{q}_n) = 1 - \prod_{i=1}^n \bar{q}_i \quad (1)$$

and the aggregate success probability is $\prod_{i=1}^n \bar{q}_i = 1 - P(\bar{q}_1, \dots, \bar{q}_n)$. This is a weakest link technology in that failure by any one firm leads to overall failure. Were all firms to pose the same risk, then we could write $\bar{q}_i = \hat{q}$ so that $P(\bar{q}_1, \dots, \bar{q}_n) = 1 - \hat{q}^n$. Denote the probability sum as $n\hat{q}$.

However, suppose $\hat{q}$ and δ are appropriately chosen such that firm 1 had success probability $\hat{q} + \delta$, firm 2 had success probability $\hat{q} - \delta$, and remaining firms continued to have success probability $\bar{q}_i = \hat{q}$. The probability sum remains $(n-2)\hat{q} + (\hat{q} + \delta) + (\hat{q} - \delta) = n\hat{q}$. Then the overall probability of invasion becomes $P(\bar{q}_1, \dots, \bar{q}_n) = 1 - \hat{q}^{n-2} (\hat{q} + \delta)(\hat{q} - \delta) = 1 - \hat{q}^n + \hat{q}^{n-2} \delta^2 \geq 1 - \hat{q}^n$, with strict inequality whenever $\delta > 0$. Indeed, it is readily shown that the inequality applies over the simplex $S = \{(\bar{q}_1, \dots, \bar{q}_n) : \bar{q}_i \geq 0 \forall i \in \Omega_n, \sum_{i=1}^n \bar{q}_i = n\hat{q}\}$, i.e. $P(\bar{q}_1, \dots, \bar{q}_n) \geq 1 - \hat{q}^n \forall (\bar{q}_1, \dots, \bar{q}_n) \in S$ with strict inequality whenever coordinate values are not common². This means that an increase in the dispersion of individual success probabilities, subject to the sum constraint $\sum_{i=1}^n \bar{q}_i = n\hat{q}$, decreases the overall success probability. The weakest link technology ensures that firms with a comparatively low individual success probability do harm to the overall success probability that is difficult to compensate for by the existence of firms with a comparatively high individual success probability.

As an illustration, Horan and Lupi (2005b) report that about 500 round trips take place in the Great Lakes region by transoceanic vessels. Over a 20 year time frame, suppose that

$n = 500(20) = 10,000$ and $n\hat{q} = 10,000\hat{q} = 9998$ so that $\hat{q} = 0.9998$. If all $\bar{q}_i$ are equal then the probability of invasion is $1 - (0.9998)^{10,000} \approx 0.86469$. If $\bar{q}_i = 1 \forall i \in \{1, \dots, 499\}$ for each of these 20 years and $\bar{q}_{500} = 0.9$, then the probability of invasion is $1 - (1)^{499 \times 20} (0.9)^{20} = 0.87842$. The invasion probability is somewhat larger if the individual failure probability is concentrated in one firm when compared with equal dispersion across all firms.

In general, suppose that $n\hat{q} = n - \alpha$ with $0 \leq \alpha \leq 1$. If all $\bar{q}_i$ values are equal at $\hat{q} = 1 - \alpha/n$ then the probability of invasion by year t is $P(\bar{q}_1, \dots, \bar{q}_n) = 1 - (1 - \alpha/n)^{nt}$, with

$$\lim_{n \rightarrow \infty} 1 - \left(1 - \frac{\alpha}{n}\right)^{nt} = 1 - e^{-\alpha t} \quad (2)$$

A first-order Taylor series approximation around $\alpha t = 0$ yields $1 - e^{-\alpha t} \approx 1 - (1 - \alpha t) = \alpha t$. Alternatively, if $\bar{q}_1 = 1 - \alpha$ and $\bar{q}_i = 1 \forall i \in \{2, 3, \dots, n\}$ then $\lim_{n \rightarrow \infty} P(\bar{q}_1, \bar{q}_2 = 1, \dots, \bar{q}_n = 1) = 1 - (1 - \alpha)^t (1)^{(n-1)t} \approx \alpha t$. So, as with the numerical illustration above, when αt is in the neighborhood of zero then the discrepancy should be small whereas when αt is in the neighborhood of 1 then the discrepancy can be large. In that case, for $\alpha = t = 1$ then $1 - e^{-\alpha t} \approx 0.6321$ while $1 - (1 - \alpha)^t (1)^{(n-1)t} = 1 - (1 - \alpha) = 1$.

3. Linear constraint

In this section we will first lay out what is essentially the trading problem in Horan and Lupi (2005b). We will then present alternative specifications of the social planner's problem. The optimality conditions for these problems will then be contrasted to show, as Horan and Lupi (2005b) did, that a linear risk constraint is generally inefficient. Throughout we assume there is just one invasive species of concern.

Trading is likely to be in maximum allowable failure probabilities or maximum allowable levels of observable activities that are associated with failure, rather than in success probabilities. For this reason the analysis below will work with q_i and not with individual success probability $\bar{q}_i$. The trading problem laid out in Eq. (5) of Horan and Lupi (2005b) may be characterized as follows. Pollution control costs are $c_i(q_i)$, a (likely distinct) decreasing and convex function for the i th firm. Each vessel owner chooses its own failure probability q_i , a probability level correctly discerned by the monitoring regulator. The firm receives a failure probability allowance endowment of q_i^0 and the equilibrium market price of a unit of the risk instrument is ρ . Before trading takes place, the social planner chooses the total permit number Q , such that $\sum_{i=1}^n q_i^0 = Q$ so that the instrument's market price depends on Q , or $\rho = \rho(Q)$.

Assuming interior solutions and that the risk levels bind, then the firm's problem is to

$$\min_{q_i} c_i(q_i) + \rho \times (q_i - q_i^0) \quad \text{s.t. } q_i \leq q_i^0 \quad (3)$$

This is consistent with minimizing the firms' joint costs subject to the total permit constraint, i.e.,

$$\min_{(q_1, \dots, q_n)} \sum_{i=1}^n c_i(q_i) + \rho \times \left(\sum_{i=1}^n q_i - Q\right) \quad (4)$$

² There is a large literature on the theory of permutation symmetric functions such as $P(\bar{q}_1, \dots, \bar{q}_n)$ on a simplex domain such as S . Inequality $P(\bar{q}_1, \dots, \bar{q}_n) \geq 1 - \hat{q}^n$ is an example of a majorization relation, a set of tools widely encountered in the theory of measuring species diversity (Marshall and Olkin, 1979; Tong, 1983).

The first-order conditions for Eqs. (3) and (4) are

$$\frac{dc_i(q_i)}{dq_i} = -\rho(Q) \quad \forall i \in \Omega_n, \quad (5)$$

where interior solutions are assumed. Write $q_i^l = g_i[\rho(Q)]$ as the market clearing solution to this optimality condition, where superscript l is to identify the linear nature of the constraint in Eq. (4). The final step in the Horan and Lupi linear framework is to optimize over Q .

True social cost will depend on the invasion probability rather than on the sum of the failure probability allowance endowments, Q . Thus, rather than problem (4), the constrained social objective is to minimize the cost of protecting against invasion subject to a given probability of invasion. Labeling Φ as the invasion probability, the social cost minimization problem may be written as

$$\begin{aligned} & \text{Min}_{(q_1, \dots, q_n)} \sum_{i=1}^n c_i(q_i) \quad \text{subject to } P(\bar{q}_1, \dots, \bar{q}_n) = \Phi \\ & = \text{Min}_{(q_1, \dots, q_n)} \sum_{i=1}^n c_i(q_i) \quad \text{subject to } \prod_{i=1}^n (1 - q_i) = 1 - \Phi \\ & = \text{Min}_{(q_1, \dots, q_n)} \sum_{i=1}^n c_i(q_i) \quad \text{subject to } \sum_{i=1}^n \ln(1 - q_i) = \ln(1 - \Phi) \\ & = \text{Min}_{(q_1, \dots, q_n)} \sum_{i=1}^n c_i(q_i) + \lambda \times [\ln(1 - \Phi) - \sum_{i=1}^n \ln(1 - q_i)], \end{aligned} \quad (6)$$

where λ is the constraint Lagrangian multiplier and shadow value of a unit increase in $\ln(1 - \Phi)$. Of course λ depends on Φ , or $\lambda = \lambda(\Phi)$. The first-order conditions are

$$(1 - q_i) \frac{dc_i(q_i)}{dq_i} = -\lambda(\Phi) \quad \forall i \in \Omega_n, \quad (7)$$

with solutions q_i^m . Here, superscript m is to identify the multiplicative nature of the constraint representing the overall probability of success in avoiding an invasion, i.e. $\prod_{i=1}^n (1 - q_i) = 1 - \Phi$ is multiplicative in individual success probabilities.

If permit trading, as represented by Eqs. (3) and (4), is to achieve the least-cost conditional on the given invasion probability Φ , then Eqs. (5) and (7) should deliver the same solution values. Equating these optimality conditions requires $q_i^m = q_i^l = 1 - \lambda/\rho$, i.e., that firms make common choices if the market trading problem is to be socially optimal³. A common value for socially optimal individual success probabilities is unlikely since the only conditions on firm cost functions are that they be increasing and convex. In addition, given that the probability of failure is equal to $1 - \prod_{i=1}^n (1 - q_i)$, satisfying $\sum_{i=0}^n q_i^0 = Q$ for any given value of Q does not guarantee that the targeted failure probability will be met.

4. Incentives

Given problems with trading under the linear risk constraint, Horan and Lupi turned to second-best trading programs. Instead, we ask how one might implement a first-best trading program. Can a trading mechanism be constructed that does

minimize cost subject to the invasion risk constraint? The answer is 'yes' and the transformation in Eq. (6) reveals this. Writing $z_i = \ln(1 - q_i)$ then $1 - q_i = e^{z_i}$, $c_i(q_i) = c_i(1 - e^{z_i}) \equiv \tilde{c}_i(z_i)$ and the Lagrangian for the social welfare problem can be presented as

$$\text{Min}_{(z_1, \dots, z_n)} \sum_{i=1}^n \tilde{c}_i(z_i) + \lambda \times [\ln(1 - \Phi) - \sum_{i=1}^n z_i]. \quad (8)$$

There should not be any additional practical problems in trading log probabilities z_i relative to probabilities as quantified by q_i or $\bar{q}_i$; it is just a matter of getting used to how the instrument is presented for trading.

There remains the issue of specifying the instrument to be traded such that one buys permits to have a larger failure probability or take a riskier observable action, parallel to problem (3) above. Define $y_i = -z_i = -\ln(1 - q_i)$ so that $y_i \geq 0$. Also define $Y = -\ln(1 - \Phi)$. Then, parallel to Eq. (3), the private optimization problem can be specified as

$$\text{Min}_{y_i} \tilde{c}_i(y_i) + \lambda \times (y_i - y_i^0) \quad \text{s.t. } y_i \leq y_i^0. \quad (9)$$

where the firm's cost $\tilde{c}_i(y_i)$ is defined by $\tilde{c}_i(y_i) \equiv c_i(1 - e^{-y_i})$.

A permit market allowing one-for-one trading in y_i minimizes the sum of costs associated with attaining the constraint that the log of the probability of no invasion is at least $\ln(1 - \Phi)$. This is because the log transformation has provided us with a problem that is isomorphic to that of permit trading for uniformly mixed pollutants, where an interior optimum requires marginal costs to be common (Montgomery, 1972). Linearization is possible under independent individual success probabilities. For a weakest link technology and independence among risks, the logs of individual success probabilities may be viewed as mixing uniformly to give the aggregate success probability. This single modification to the Horan and Lupi trading system brings the weight of the large literature on permit trading efficiency down in support of the novel and potentially important idea that they have developed.

5. Conclusion

Risk permit trading could conceivably have many applications beyond waterway access by transoceanic vessels. These might include limitations on the use of transgenic species where again invasive species is the concern, and on the use of antibiotics where resistance is the concern. Inefficiencies from implementing a risk permit trading scheme that is linear in firm success probabilities rather than linear in the log of these probabilities are likely to be small or even negligible in many cases, but could be larger in other cases. If the linear risk sum constraint were thought to be more practical to implement, our analysis can be seen as a motive for restricting large positions in risk permits for any one vessel.

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³ Notice that the left hand side of Eq. (7) is an increasing function of q_i , so convexity is not a concern.

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