TRADABLE RISK PERMITS TO PREVENT FUTURE INTRODUCTIONS OF ALIEN INVASIVE SPECIES INTO THE GREAT LAKES

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Introduction

Invasive alien species (IAS) - species that establish and spread in ecosystems to which they are not native - are argued to be the second-most important cause of biodiversity loss worldwide (Holmes; U.S. EPA 2001). Without natural predators, parasites, and/or pathogens to help control population growth, IAS frequently out-compete or prey on native species. They cause or spread diseases to cultivated plants, livestock and human populations. They often encroach on, damage or degrade assets (e.g., power plants, boats, piers, and reservoirs). The associated economic impacts can be significant (Perrings et al. 2000).

IAS have had a significant impact on the Great Lakes. At least 145 IAS have been introduced into the Great Lakes since the 1830's, with one-third being introduced during the past thirty years – likely in response to increased shipping in the St. Lawrence Seaway (ANS State Management Plan, 2001; GLC Resolutions, 2000). Only about ten percent of introduced species have caused any damage (Mills et al. 1993) but, for those that have, the impacts are typically extensive (U.S. EPA 2001; MDEQ 2001; Coscarelli and Bankard 1999; Reeves 1999). For example, zebra mussels alone are predicted to create five billion dollars in damages over the next ten years (MDEQ, 2000).

Management of IAS includes several options: prevention of new species introductions (treating IAS as a form of ‘biological pollution”), eradication following introduction, containment or control of IAS populations (e.g., IPM), or adaptation. Historically, efforts have focused on eradication and post-invasion control, with comparatively little effort being committed to preventive measures. But that is changing, possibly due to the recognition that most new IAS introductions are the result of human activities. In the Great Lakes, commercial shipping has been implicated in over 60% of new introductions since 1960 (Mills et al. 1993), with ballast water being the primary pathway.[1] Ships carry water in their hulls as ballast to maintain stability and integrity. Species may be inadvertently transferred into or out of a ship as ballast water levels are adjusted at port to account for changes in cargo, or in transit to improve stability or to alter hull depth.

Oceanic ballast water exchange has been the predominant preventive approach to IAS in the Great Lakes, becoming mandatory in 1993 with the implementation of the U.S. Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, and later by the U.S. National Invasive Species Act of 1996 and the Canadian Shipping Act of 1998 (Reeves 1999).[2] All vessels entering the Great Lakes with ballast on board (BOB) are required to exchange ballast at sea beyond the Exclusive Economic Zone (EEZ) in a depth of at least 2,000m, so that ballast salinity levels are raised to 30ppt (ocean salinity levels range between 34 to 36ppt). This ballast must then be retained for the duration of the voyage into the Great Lakes (NRC 1996). Ballast retention is the primary prevention measure, while oceanic exchange is secondary. For instance, if some ballast exchange was to take place in the Great Lakes, e.g. to pass through a lock or for safety reasons, it is thought that organisms that might survive in the fresh or brackish waters of the Great Lakes could not survive in the high saline levels that would result from the oceanic exchange, and vice versa (Rigby and Taylor 2001).[3]

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[1] Solid ballast and hull-fouling were once important causes of introductions. But solid ballast is now seldom used, and steel hulls combined with anti-fouling techniques have greatly diminished introductions due to hull-fouling.

[2] In 2001, the State of Michigan enacted Public Act 114 that requires reporting of ballast management and ties eligibility for state grants, awards, and loans to satisfactory ballast management.

[3] The primary purpose of increasing salinity levels in the tanks is not necessarily to kill freshwater organisms in the tanks, although this is a secondary effect. Rather, the intent is a 100% exchange of water and organisms, as it is felt that oceanic organisms that could survive in the Great Lakes would have already migrated there long ago. Hence, oceanic ballast exchange represents an exchange of organisms across two distinct ecological zones by which reciprocal introductions do not occur (Reeves 1999).

The success of oceanic exchange programs is unclear because new introductions have occurred since 1993 and there are known limitations to the practice of ballast water exchange. First, a vessel does not have to conduct an oceanic exchange if this is deemed to be unsafe. Hull stress increases and stability decreases during an oceanic exchange (Reeves 1999), and it is not uncommon for captains to opt out of an exchange due to safety reasons.[4] Second, ballast exchange typically does not result in a 100 percent replacement of all ballast water and sludge (Rigby and Taylor 2001; Reeves 1999). Many organisms are left in the tanks and the high salinity levels do not kill them all (Rigby and Taylor 2001; Reeves 1999). A third limitation is that the regulations do not apply to vessels entering the Great Lakes with no ballast on board (NOBOB), which typically carry tons of unpumpable sludge at the bottom of their hulls. This sludge may be home to many foreign organisms that can be introduced when the ship initially takes on ballast at its first stop in the Great Lakes, and/or when it exchanges ballast at subsequent ports. Farley (1996) estimates that ships entering the Great Lakes with a NOBOB status accounted for 84% of the discharged ballast containing foreign water in 1995.

The limitations of current regulatory approaches are now generally recognized, as is the need for new policy options that promote both safety and cost-effectiveness (NRC 1996; Rigby and Taylor 2001). A number of technological alternatives to ballast exchange currently exist, but the cost-effectiveness of each is thought to vary widely across vessels due to heterogeneities in vessel characteristics (Rigby and Taylor 2001). This implies that uniform technology standards would be inefficient, and that performance-based approaches that allow each vessel to make individualized choices make more economic sense.

Pollution trading is a performance-based approach that is gaining increasing acceptance as an efficient means for achieving emissions reductions, and trading has successfully reduced the costs

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[4] In 1998, the *Flare* broke in half on its way to Montreal, and ballast exchange may have contributed to this.

of controlling various forms of air and water pollution in the U.S. and other developed countries (see e.g., Baumol and Oates 1988; Hahn 1989; Hanley et al. 1997; Tietenberg 1995). Could an IAS tradeable permit program offer similar economic gains? The answer depends on how well the program is designed to realize the potential gains.

Two features of vessels' biological emissions complicate matters. First, not every vessel will actually emit a species, yet ex ante each vessel is a potential emitter and so society is expected to benefit from all vessels undertaking biosecurity actions to reduce the probability of an invasion. Second, biological emissions are highly stochastic and essentially unobservable given current monitoring technologies – much like nonpoint source pollution (Shortle and Dunn 1986). So there is no way to directly observe or otherwise indirectly measure if a vessel is responsible for an introduction.

Because there is no readily available method of directly measuring IAS emissions, they cannot be directly traded. This is in contrast to conventional pollution permit programs, in which pollution permits define allowable emissions for the permit holder. In consequence, a fundamental issue in the design of IAS trading programs is what exactly it is that vessels will trade. One option is a performance proxy – estimates of emissions, where the estimates are derived from a model that relates vessel characteristics and observable biosecurity investments to emissions estimates.[5] In most cases, an emissions estimate is more accurately described as the probability of a species introduction by the vessel.

We examine the design and efficiency of a tradeable permit system for IAS biological pollution. We begin by developing a model of IAS invasions. Next, we derive the features of a first-best allocation of biosecurity efforts and show that a permit system based on a risk proxy

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[5] Another option would be observable biosecurity (input) choices by the vessel, which has been suggested for a basis for tradeable permit markets involving nonpoint sources (Shortle and Abler 1997; Hanley et al. 1997).

cannot be first-best. We then illustrate the features of a second-best market. This is followed by an application to shipping in the Great Lakes, where we compare the cost-effectiveness of trading versus command and control. The final section concludes and offers recommendations.

A model of IAS invasions

The model we adopt builds on that of Horan et al. (2002). Each vessel entering the Great Lakes is considered to be a potential carrier or vector of biological pollution. Individual vessels make a variety of biosecurity choices affecting the likelihood of species introductions. In the case of commercial shipping these choices might include the effort involved with ballast water exchange, the number and location of stops, the time at sea, and the use of biocides, filtering, and heat. The ith vessel's choices are denoted by the $(1\times m)$ input vector x_i (with jth element x_{ij}). Many inputs will be "lumpy" investments, although we consider them to be continuous for now. Biological pollution control costs are a function of the vessel's biosecurity choices, $c_i(x_i)$.

The biomass of species s (s=1,...,S) introduced in the given habitat by firm i is denoted e_{is}. A firm cannot control e_{is} with certainty. Introductions are random due to the influence of stochastic variables that are not directly under the firm's control (e.g., environmental drivers), although the probability of a particular level of biomass emissions is conditional on the firm's biosecurity choices. The probability that e_{is} is introduced, conditional on input choices and firm characteristics (b_i) is $p_{is}(e_{is}| x_i, b_i)$.

A species that is introduced may or may not establish and spread (invade), and cause ecological and economic damages. Conditions, including the *in situ* control regime (which we take here as given), must be right for a successful invasion. We assume damages only occur from a successful invasion. Such an outcome occurs with some probability, conditional on the scale of the introduction and also location and habitat characteristics (e.g., predators and food sources), denoted by l. The probability that an introduction e_{is} leads to a successful invasion is denoted $\Pr_s(survival \mid e_{is}, x_i, l)$, and is increasing in e_{is}. A firm's biosecurity choices also influence this probability to the extent that they influence the quality of an introduction. For instance, a species may be introduced in either a healthy or a weakened state, with the state of health being directly influenced by a firm's biosecurity choices. Accordingly, for discrete levels of e_{is}, the probability that introductions of species s by firm i lead to an invasion is $q_{is}(x_i, b_i, w) = \sum_{e_{is}} \Pr_s(survival \mid e_{is}, x_i, l) p_{is}(e_{is} \mid x_i, b_i)$. This specification assumes that invasions arise via particular firms and that the probability of an invasion via one firm is independent of introductions by other firms. This may be a simplification for some cases in which the alien population depends on a large number of introductions to become established in the new habitat. But it is realistic for species that are fairly well-suited to the new ecosystem and can establish with only small numbers (e.g., invasive pathogens).

Because a species is able to proliferate *in situ* once it has invaded, we assume a species can only invade once and that the marginal damages of further invasions of the same species is zero. This is in contrast to many pollution problems in which the current level of emissions matters. It is analogous to pollution problems in which the marginal damage cost of pollution falls to zero once the assimilative capacity of the environment has been exceeded. A species invasion is a Bernoulli event: an invasion either occurs or it does not occur. The probability of an invasion of species s via any one of n firms is

$$(1) \quad P_s(x_1, ..., x_n) = P_s(Z_s \geq 1) = 1 - P(Z_s = 0) = 1 - \prod_{i=1}^{n}(1 - q_{is}(x_i, b_i, l))$$

where Z_s represents the number of times that species s invades a given ecosystem. The probability

P_s is decreasing in biosecurity measures that make introductions less likely and increasing in biosecurity measures that make introductions more likely. The probability P_s is also increasing in the number of firms. As $n \rightarrow \infty$, invasion becomes a virtual certainty (i.e., $P_s \rightarrow 1$). This is because IAS control in this model depends on the least effective provider, representing a 'weakest link' public good (Perrings et al., 2002).

The (present value of) economic damages due to an invasion by the *s*th species are $D_s(\gamma_s)$, where γ_s is a random variable reflecting uncertain damage costs.[6] At least some of the random factors influencing the probability of survival may also influence damages. For instance, stochastic environmental variables that affect the probability that an introduced species will establish and spread may also influence its impact on the ecological services provided by the host system. Denote the common (sub-) set of random variables influencing both survival and damages by θ_s, and define the probability of survival, conditional on the value of θ_s, by $P_s(x_1,...,x_n \mid \theta_s)$. Defining E as the expectations operator over all stochastic variables, expected damages are given by

$$(2) \qquad E\{D(x_1,...,x_n)\} = \sum_{s=1}^{S} E\{D_s P_s(x_1,...,x_n \mid \theta_s)\}$$

Ex ante efficient (first-best) management of biological pollution

Ex ante efficient biosecurity measures minimize the expected social cost of biological pollution and its control[7]

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[6] The management response to the invasion is taken as given here, although a more complete model would consider the tradeoffs between prevention and mitigation efforts.

[7] Perrings et al. (2000) point out that the probabilities of invasion may be quite small and the associated damages quite large, which may give rise to non-convexities. Moreover, managers might not make decisions according to expected utility theory in such instances, instead making decisions based on a reference point. Shackle's (1969) theory of decision-making under uncertainty (ignorance) is consistent with a reference point approach, and Horan et al. (2002) illustrate that making decisions in this fashion can be equivalent to using the expected utility model with subjective weights applied to the reference point.

(3) $$\min_{x_{ij}\ \forall i,j} \sum_{i=1}^{n} c_i(x_i) + E\{D(x_1,\ldots,x_n,\Omega)\}$$

The necessary conditions for an interior solution can be written as

(4) $$\frac{\partial c_i}{\partial x_{ij}} = -E\{\frac{\partial D}{\partial x_{ij}}\} = -\sum_{s=1}^{S}[E\{D_s\}E\{\frac{\partial P_s}{\partial x_{ij}}\} + \operatorname{cov}\{D_s, \frac{\partial P_s}{\partial x_{ij}}\}] \quad \forall i, j$$

Condition (4) states that the marginal cost of undertaking a particular action (the left hand side (LHS)) optimally equals the marginal expected benefits (i.e., the reduction in damages) of the action (the right hand side (RHS)). The marginal expected benefits include both mean (the first RHS term) and risk (the second RHS term) impacts. The risk impacts occur because the specific choices made by each firm have uncertain effects on the likelihood of adverse environmental outcomes (e.g., see Shortle and Dunn 1986). The covariance term vanishes if $q_s \in \varnothing$. Further interpretations of (4) are provided by Horan et al. (2002).

A Model of Trading

Consider a tradeable permit system where permits are denominated in terms of the likelihood or probability of an IAS introduction p_{is}, or the probability of an invasion q_{is}. Both of these probabilities are ex ante measures of environmental performance, although q_{is} more closely relates a vessel's biosecurity choices to environmental damages when some choices affect q_{is} directly (Turvey 1963). We therefore consider q_{is} as the relevant permit base to consider. Since q_{is} is a performance-based measure, vessels attempting to achieve a particular level of q_{is} are given the flexibility to reduce their expected environmental pressures in the most cost-effective way, which also reduces the expected social costs of control.

A probability-based, or risk-based, permit system would be somewhat analogous to existing point-nonpoint trading systems designed to incorporate nonpoint sources of pollution, such as agriculture, into water quality improvement programs. Permits for these programs are denominated in terms of expected (as opposed to actual) emissions (Horan 2001; Malik et al., 1993; Horan et al. 2002), which are calculated by a model that links on-site management practices and farm characteristics with expected changes in water quality.[8] In the case of IAS pollution, models could be developed to estimate the probability of an invasion, q_{is}, based on firm characteristics and management practices. This is an emerging area, with many researchers trying to identify species that are candidates for invasion and the likelihood of such invasions (Ricciardi and Rasmussen 1998; Peterson and Vieglais 2001).

A tradeable permit market works by providing each vessel with risk permits for each potential invader, denoted r_{is0}, and allowing vessels to trade the permits among themselves. The only requirement is that the level of risk actually generated by each vessel must not exceed the vessel's permit holdings. Denote the market-clearing price of the risk permits by u_r. Vessels will choose biosecurity measures and risk permit holdings, r_{is}, to minimize costs,

$$(5)\qquad \begin{aligned} &\underset{x_i, r_{is}}{Min} \quad c_i(x_i) + \sum_s u_s(r_{is} - r_{is0}) \\ &s.t. \quad q_{is} \le r_{is} \end{aligned}$$

Assuming the constraint can be satisfied as an equality, vessel i's problem can be written as

$$(6)\qquad \underset{x_i}{Min} \quad c_i(x_i) + \sum_s u_s(q_{is}(x_1,\ldots,x_n) - r_{is0})$$

The resulting first order conditions are

$$(7)\qquad \frac{\partial c_i}{\partial x_{ij}} = -\sum_s u_s \frac{\partial q_{is}}{\partial x_{ij}} \qquad \forall i,j$$

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[8] Examples of agricultural nonpoint pollution models abound, including the Erosion Productivity Impact Calculator (EPIC), the Soil and Water Assessment Tool (SWAT), the Agricultural Non-Point Source Pollution Model (AGNPS), the Hydrologic Simulation Program –Fotran (HSPF), and the Generalized Watershed Loading Function (GWLF).

The market solution is determined by condition (7) along with the market clearing conditions $\sum_i q_{is} = \sum_i r_{is0} \;\; \forall s$. Comparison of condition (7) with condition (4) indicates that the market solution will only be efficient if the market clears at the following set of permits prices

$$(8) \qquad \sum_s u_s \frac{\partial q_{is}}{\partial x_{ij}} = \sum_{s=1}^{S} [E\{D_s^*\}E\{\frac{\partial P_s^*}{\partial x_{ij}}\} + \mathrm{cov}\{D_s^*, \frac{\partial P_s^*}{\partial x_{ij}}\}] \quad \forall i,j$$

where the starred (*) terms on the right-hand-side (RHS) of (8) indicate that these relations are evaluated at their optimal levels. Condition (8) represents a series of $n´m$ equations in S unknowns. If $n´m>S$, then the system is overdetermined: a solution will not exist and the market cannot be efficient (see Shortle and Dunn 1986 for an analogous result in the context of reducing estimated nonpoint emissions). If $n´m<S$, then the efficient outcome can be attained.

To see why the market may be inefficient, even when the total number of permits is set optimally, consider the following condition which is sufficient for satisfying (8)

$$(9) \quad u_s \frac{\partial q_{is}}{\partial x_{ij}} = [E\{D_s^*\}E\{\frac{\partial P_s^*}{\partial x_{ij}}\} + \mathrm{cov}\{D_s^*, \frac{\partial P_s^*}{\partial x_{ij}}\}] \qquad \forall s,i,j$$

Using (1), condition (9) can be written as

$$(10) \qquad u_s = E\{D_s^*\}E\{(1 - P_s^{-i*})\} + \frac{\mathrm{cov}\{D_s^*, \partial P_s^* / \partial x_{ij}\}}{\partial q_{is} / \partial x_{ij}} \qquad \forall s,i,j$$

where $P_s^{-i} = 1 - \prod_{k \neq i}(1 - q_{ks}(\bullet \,|\, q_s))$ is the aggregate probability (conditional on q_s) that species s will invade from any vessel other than vessel i. The two terms on the RHS of (10), respectively, reflect the mean effects of a vessel's reduction in the probability of an invasion, and the risk-effects associated with a vessel's input use. The market-clearing price is overdetermined in condition (10) for two reasons. First, the mean marginal impact of a vessel's efforts to reduce the probability of an invasion, $E\{(1 - P_s^{-i*})\}$, differs for each vessel. Vessel-specific probabilities of invasion are not perfect substitutes for one another. It is therefore not efficient for vessels to be trading permits on a one-for-one basis. This result is consistent with those of traditional pollution permit trading markets, where it is well-known that 1:1 trades are inefficient when firms' emissions have differential marginal environmental impacts (McGartland and Oates, 1985; Montgomery, 1972; Tietenberg, 1995a). It would be more efficient if trades were evaluated on a trade-specific basis. Of course, this would increase the transactions costs of trading, ultimately leading to fewer trades and larger program costs.

The second reason equation (14) is overdetermined is the covariance term. This term represents the risk-effects of choosing biosecurity measures to control the probability of an invasion as opposed to expected damages. The problem is that when firms make choices to reduce the probability of an invasion, there may be unintended impacts on damages since the firm has no incentives to account for these. Therefore, a trading program based on the probability of an invasion cannot satisfy (5) cost-effectively when $q_s \notin \emptyset$ because it does not provide firms with incentives to consider all of the impacts of their choices on damages.

A first-best trading program (i.e., one that satisfies (5) cost-effectively) when $q_s \notin \emptyset$ would involve firms trading permits (or requirements) based on biosecurity investments (Shortle and Abler 1997). Such a program could be designed to provide firms with the correct incentives to consider the impacts of their choices on damages. But such a program would require the use of $m \times S$ separate permits being traded at $n \times m \times S$ rates. This would clearly be administratively complex if not infeasible. Moreover, in practice many of the biosecurity choices are 'lumpy' investments that are not easily tradeable. Because of these difficulties we now turn to a simpler, second-best trading program.

Second-best management

Consider a market is which trades between vessels can only take place on a 1:1 basis, and there is only one type of permit: a permit restricting the probability that a vessel introduces *any* species, $q_i(x_i, b_i, l)$. The restriction of 1:1 trading is analogous to some existing trading systems in other arenas, but as described above it also implies certain inefficiencies due to the fact that each vessel has a different marginal environmental impact. Even if each vessel had identical marginal environmental impacts, such a trading scheme could only be second-best due to the covariance effects described above. The restriction of a single permit reduces efficiency when introductions of different species have different damage impacts, but such a system is easier to manage. Moreover, in practice it may not be possible to identify all possible invaders and also the likelihood of invasion ex ante (Horan et al. 2002), and so this permit system may reduce information requirements on the part of both vessels and the administrator.

Another complexity to deal with is the reality that the complete state space and associated probabilities, for both potential invaders and potential damages from known and unknown potential invaders, cannot be identified ex ante. Accordingly, the ex ante efficient problem (3) is not well-defined. A reasonable alternative is to pursue a cost-effective allocation of biosecurity controls based on probabilistic information that can be developed subjectively.

Cost-effectiveness is a standard benchmark for analyzing pollution control resource allocations. Useful notions of cost-effectiveness for biological pollution control must consider the unobservable and stochastic nature of species introductions, and the stochastic nature of invasions. Since damages are presently unknown and perhaps unknowable for many species, a useful approach to defining the least-cost allocation uses probabilistic constraints of the form

$$(11) \qquad P_s(x_1, ..., x_n) \le \Phi_s \qquad \forall s \in \hat{S}$$

where $0 \leq \Phi_s \leq 1$ and $\hat{S}$ (with $\hat{S} \subseteq S$) represents a set of target species upon which controls are based.[9] This "safety-first" approach, which has received attention in economic research on the control of stochastic pollution (Beavis and Walker 1983; Lichtenberg and Zilberman 1988; Lichtenberg et al. 1989), is consistent with the goals of the International Maritime Organization (IMO). The IMO has accepted that reducing risk (and not trying to eliminate it) should form the basis for the development of new mandatory ballast water management instruments (Rigby and Taylor 2001).[10] The focus on target species is an approach that has been formally adopted by the Australian Ballast Water Management Council, and it is considered to be a *de facto* approach in ballast water management programs in the Great Lakes (although some might argue that the Great Lakes approach is non-target oriented) (Rigby and Taylor 2001).

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[9] When damages are known, an interesting cost-effectiveness concept when invasions are stochastic is an upper bound on expected damage costs $E\{D(x_1,..., x_n)\} \leq T$, where T is the upper bound. Unless $q_s \in \emptyset$ (i.e., the null set, so that $E\{D\} = \sum_{s=1}^{S} E\{D_s\} P_s(x_1,..., x_n)$), then only in this case will allocations that achieve the target at least cost be unambiguously more efficient than allocations that achieve the target at higher cost (Shortle 1990; Horan 2001).

[10] Technically, the IMO is promoting the use of the precautionary principle of minimizing risk (Rigby and Taylor 2001). However, it also realizes that risk cannot be completely eliminated, suggesting that it understands the costs of attaining such an objective would be too high. Our focus on a safety-first criterion therefore appears to be consistent with their objectives.

An ex ante cost-effective allocation of biosecurity measures minimizes the expected cost of biological pollution control (*TC*) subject to (11) and also subject to vessel responses to the permit system. There are two ways to determine the number of permits that minimize *TC*, subject to (11) and vessel responses. A primal approach would be to choose the optimal number of total permits, $R = \sum_i r_{i0}$ and distribute the permits according to some rule.[11] In contrast, a dual approach is to take as given the vessels' input demand functions that result from the vessels' first order conditions, $x_i(u)$, where u is the equilibrium permit price, and choose permit prices optimally. Specifically, the objective function for the dual approach is[12]

$$(12) \qquad \begin{aligned} &\underset{u}{Min} \;\; TC = \sum_{i=1}^{n} c_i(x_i(u)) \\ &\text{s.t.} \;\; P_s(x_1(u),\ldots,x_n(u)) \le \Phi_s \qquad \forall s \in \hat{S} \end{aligned}$$

The first order conditions for this problem are

$$(13) \qquad \sum_i \sum_j \frac{\partial c_i}{\partial x_{ij}} \frac{\partial x_{ij}}{\partial u} = -\sum_s \sum_i \sum_j l_s \frac{\partial P_s}{\partial x_{ij}} \frac{\partial x_{ij}}{\partial u}$$

along with the constraint (11), where l_s is the shadow value of the *s*th constraint. Using the vessels' first order conditions, equation (13) can be solved for the optimal permit price

$$(14) \qquad u = \frac{\sum_s \sum_i \sum_j l_s^* \frac{\partial P_s^*}{\partial x_{ij}} k_{ij}^*}{\sum_i \sum_j \frac{\partial q_i^*}{\partial x_{ij}} k_{ij}^*}$$

where $k_{ij}^* = (\partial x_{ij}^* / \partial u) / \sum_i \sum_j (\partial x_{ij}^* / \partial u)$, and the superscript (*) indicates that all variables are

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[11] Options range from public auctions to free-of-charge assignments. See Hanley et al. (1997) for discussion of options and issues.

[12] If the permit system is not denominated according to different species (which would be difficult to administer if the number of target species was large) then in the cost-effective solution it will not be possible to satisfy each constraint in (11) as an equality.

evaluated at their optimal values as the solution to (12).

Interpreting k_{ij}^* as a weight (since $\sum_i \sum_j k_{ij}^* = 1$), the numerator of the expression for u is the marginal social cost of biosecurity controls, averaged across all species, vessels and biosecurity choices. The denominator is the marginal impact of bioscurity controls on the likelihood of invasion, averaged across all vessels and biosecurity choices. The averaging of impacts across all species, vessels and biosecurity choices in equation (14) is a consequence of the restrictions of 1:1 trading across vessels. Another inefficiency is implied by the focus on *all* species as opposed to individual species. In consequence, the second-best price u does not give firms incentives to exploit differences in their relative marginal environmental impacts as a differentiated price system would. The degree to which this creates inefficiencies depends on the degree of heterogeneity of marginal impacts and on correlations between key environmental and cost relationships.

An application to Great Lakes shipping

Each year, approximately 200 – 300 vessels enter the Great Lakes and account for 400-600 round trips in and out of the region. More than 70 percent of entering vessels are of international flag and are engaged in the ‘triangle trade’, taking grain from the Great Lakes to the Mediterranean, and then to Northern Europe (Reeves 1999). Major overseas markets are Western Europe, the Baltics, the Mediterranean, and the Middle East. A number of other vessels, known as “lakers”, operate exclusively on the Great Lakes. While lakers may be responsible for spreading IAS within the Great Lakes, they are not responsible for new introductions into the region. Our focus is on vessels that pose a threat of new introductions.

Vessel heterogeneity is defined according to each vessel’s deadweight tonnage (DWT). Magma (2003) provides unofficial statistics on all international vessels that travel up and down the St. Lawrence Seaway. We focus on a subset of 305 international vessels, which represents the majority of Seaway vessels. According to Reeves (1999), vessels carry 15 – 30% of DWT in ballast water. We use 30% of DWT as the value of ballast water capacity, denoted b_i for the *i*th vessel, although we do not assume each vessel enters the Seaway carrying that much ballast. Rather, this value represents each vessel's potential ballast – it may enter or leave the Seaway with this much ballast or a fraction thereof. Because a tank can never be fully emptied (i.e., $b_i > 0$), this value also accounts for the unpumpable sludge in a vessel's tanks, which is particularly relevant for the majority of entering vessels that bear the NOBOB status (Reeves 1999).

The concept of target species has not been adopted in the Great Lakes as it has been in Australia (Rigby and Taylor 2001), but some potential invaders of concern have been identified, particularly from the Ponto-Caspian region which supplied approximately 70 percent of Great Lakes invaders between 1985 and 2000 (Reid and Orlova 2002). Ricciardi and Rasmussen (1998) identify the Ponto-Caspian species *Corophium spp.* (a small amphipod), Mysids (a small shrimp), and *Clupeonella caspia* (a small fish) as likely invaders capable of causing extensive damage.

The base probability that a vessel *i* will transport species *s* into the Great Lakes, for the case where the vessel adopts no biosecurity measures, is denoted k_{is}. This value is directly proportional to the ballast (or sludge) that the vessel carries, $k_{is} = \alpha_{is} b_i$, where $\alpha_{is} > 0$ is a parameter: larger vessels are more likely to bring in species, *ceteris paribus*. In general, α_{is} may vary according to the vessel's trade route. But with most vessels following the triangle trade route and without detailed information on ports visited and the risks associated with specific ports, we assume this value is the same for all vessels. Assuming species *s* is introduced into the environment, the likelihood that the species will establish is denoted b_s. In the absence of biosecurity efforts, $b_s a_{is} b_i$ represents the likelihood of an invasion of species *s* by vessel *i*.

Vessels can adopt various biosecurity techniques to reduce the probability of an invasion. Filtering reduces the likelihood that species will enter or exit a vessel's ballast tanks. The effectiveness of filtering on species *s* is denoted by the function $f_{fs}(x_{if})$ (with $x_{if} \in [0,1]$ and $f_{fs}(0) = 1, f_{fs}(1) = f^L_{fs}$, where f^L_{fs} is a lower bound on f_{fs}), with x_{if} being an index that represents the effectiveness of the filtering technology, e.g., by choice of mesh size for the filter.

The survival of species in transit is affected by in-transit ballast management practices. The most promising in-transit practices are ballast exchange via continuous flushing, reballasting, heat, chemical treatments, and ultraviolet radiation (UV) (Rigby and Taylor 2001; Pollutech 1996). Reballasting is often considered dangerous, whereas ballast exchange via continuous flushing has been shown to be safer and as effective (Rigby and Taylor 2001). Chemical treatments are usually discouraged due to their high cost and also the safety and environmental hazards associated with their use (NRC 1996; Rigby and Taylor 2001; Pollutech 1996). UV is only considered to be potentially effective when it is combined with a filtering technology, but even then experts disagree as to its potential (NRC 1996). We therefore only consider ballast exchange via continuous flushing (henceforth, ballast exchange) and heat as possible in-transit practices, which Perakis and Yang (2001) also suggests are the most promising practices (along with filtering) for the Great Lakes situation.

The effectiveness of each practice will vary depending on the effort allocated to their use. For instance, the amount of ballast exchange depends on the duration of the exchange. Heat must be applied at a high enough temperature for a long enough period of time to kill everything, and this can be difficult and costly to achieve (Rigby and Taylor 2001; Pollutech 1996; NRC 1996).

As above, define the effectiveness of practice j on species s by $f_{js}(x_{ij})$ (with $x_{ij} \in [0,1]$ and $f_{js}(0) = 0, f_{js}(1) = f^U_{js}$, where f^U_{js} is an upper bound on f_{js}).[13]

Given this specification, the probability that species s invades due to the activities of vessel i is given by $q_{is} = b_s[1 - f_{Bs}(x_{iB})][1 - f_{hs}(x_{ih})][1 - f_{fs}(x_{if})]k_{is}$, where the indices B and h represent ballast exchange and heat, respectively. The function $f_{js}(x_{ij}) = m_{ij} x_{ij}^{d_{js}}$ (j=f,B,h), where m_{ij} and d_{js} are parameters that are calibrated from reported results of the effectiveness of the various ballast water management practices, under the assumption that $x_{ij} = 1$ in the experiments that generated the effectiveness data (Rigby and Taylor 2001; see Table 1).

Vessel i's variable control costs are defined by $c_i(x_i) = \sum_j w_{ij} x_{ij}$, where w_{ij} is the constant per unit cost of practice j for vessel i. Unit costs vary by ballast capacity (Rigby and Taylor 2001). Using Rigby and Taylor's cost data for cape size and container vessels (Table 2), we calibrate unit costs by vessel size, $w_{ij} = g_{ij} b_i^{r_{ij}}$. There is also a fixed capital cost associated with the use of some technologies. Fixed costs (Table 2) also depend on vessel size, $F_{ij} = \Gamma_{ij} b_i^{\mathrm{P}_{ij}}$.[14]

With multiple technologies and associated fixed costs, determining optimal allocations of control efforts requires that we solve a constrained, mixed-integer nonlinear programming (MINLP) problem. There are many ways to solve such problems, with a brute force approach being to determine an optimum for each possible combination of technology adoption choices across vessels and then comparing these optima to find the global optimum. Fortunately, many

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[13] It is necessary for the regulatory agency to have perfect knowledge of each vessel's effort levels in order to accurately gauge whether the vessel is in compliance with its permit holdings. We assume that it is possible to perfectly monitor effort levels, although in reality vessels will have incentives to mis-represent their actual effort levels.

[14] After deriving fixed costs, they are annualized using a rate of 8% over a 15-year interval to obtain the results in Table 2.

permutations can easily be eliminated from consideration. First, we have found through experimentation that it is never optimal for a single vessel to adopt two technologies. Second, many permutations can be eliminated by noticing that effort costs and effectiveness are perfectly correlated with vessel size. For instance, consider the case with only two technologies, ballast exchange and filtering. A baseline scenario might involve all vessels adopting ballast exchange. This technology has the greatest unit cost and is also the least effective of the two technologies, but might be a first choice for adoption because it also has the smallest fixed costs. The next scenario to consider would be the same as the baseline except that the largest vessel adopts filtering (with the smallest unit cost and greatest effectiveness, but also the largest fixed costs), which would have the greatest impacts on reducing both risk and costs. In the next permutation, the largest two vessels might adopt filtering, and so on. What simplifies things is that it is never optimal for a smaller vessel to adopt filtering while a larger vessel adopts ballast exchange – this would only increase costs and reduce effectiveness.[15] So such permutations (the bulk of possibilities) are ruled out. This enables us to solve and compare results from a small subset of permutations.

Results

Simulation results for several values of Φ_s are reported in Table 3 for the least cost outcome (which is the same as a highly complex first-best trading program), the permit trading market, and various uniform technological regulations. The parameter b_s is set equal to 0.1 $\forall s$ in accordance with the observation by Perrings et al. (2002) that introduced species often have about a ten percent chance of establishing a viable population in the new ecosystem. The parameter a_s is set equal to $0.000001\ \forall s$ to complete the model specification and ensure that each species has a moderate chance of invasion in any particular year when there are no policies or controls in place.

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[15] Of course, fixed costs also matter and in theory could affect this result, but random experiments support this

Specifically, each species has a 28% chance of invasion in any given year in the unregulated base case. Note that although a_s and b_s are the same for each vessel, q_{is} varies considerably by vessel since this value also depends on the vessel's size. Several patterns emerge from Table 3. First, consider the choice of technologies under the two optimally determined plans (least cost and trading). Heating is never a preferred option for any of the scenarios due to its high unit costs, which imply high overall costs when the desired level of risk is low (e.g., see the costs associated with a uniform heating requirement at even the Φ=0.1 level of risk). Second, ballast exchange is optimally used more extensively for larger allowable risk levels, as evidenced by their proportion in total control costs. As the overall level of risk (Φ) is reduced, the effort required for an effective ballast transfer becomes so high that it becomes optimal for some vessels to incur the fixed costs of filtering to take advantage of its low unit cost and high degree of effectiveness.

The second observation that can be made from Table 3 is that heterogeneity in risk across vessels is optimal even though IAS control is a weakest-link public good. This heterogeneity, measured by the coefficient of variation of the likelihoods that vessels will create an invasion of *Corophium spp*., arises to take advantage of differences in marginal costs across vessels and, in the least cost allocation, differences in vessels' marginal impacts on overall risk. Perhaps surprising is that there is greater dispersion of risk across vessels for smaller values of Φ. In order to achieve more stringent goals, more small vessels optimally increase their control efforts until their effort approaches an upper bound. The result is a bimodal distribution of effort, with larger vessels maintaining lower levels of effort, and greater heterogeneity in risk across vessels. One would expect that this bimodal distribution again becomes modal and risk heterogeneity reduced as $\Phi \rightarrow 0$.

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assumption.

A third observation from Table 3 is that the trading system performs at different levels under different levels of overall risk. When $\Phi=0.1$, control costs are 30 percent larger under trading than in the least cost allocation, while there is only a six percent difference when $\Phi=0.01$. Trading results in higher costs primarily because vessel-specific risk is traded on a one-for-one basis, so that vessels have no incentives to consider the marginal impacts of their risk on the aggregate likelihood of an invasion. Large vessels have more incentive to buy permits and increase their risk relative to smaller vessels, but the larger vessels also have the greatest marginal impact on the aggregate level of risk. These incentives therefore reduce the cost-effectiveness of the resulting allocation of controls. With the second-best risk permits, that vessels do not consider their individual marginal impacts on aggregate risk can be seen indirectly by noting that there is less risk heterogeneity under trading than in the least cost solution. The only reason for this difference is that some vessels do not take advantage of the greater marginal impacts of their effort on risk reduction, which would tend to increase heterogeneity. The inefficiencies of trading are diminished as Φ becomes smaller. The reason is that there are fewer technological/behavioral options as Φ is reduced – even in the least cost outcome more and more vessels must operate with maximum effort when more stringent goals must be satisfied, leaving less room to exploit vessel-specific differences that could otherwise lead to increased cost savings. Consequently, the least cost and trading allocations become more similar when the aggregate risk goal is lowered.

Finally, consider the results of a uniform technological requirement designed to achieve the desired level of risk. Uniform ballast exchange requirements are less costly than the uniform filtering or heat requirements when the overall level of risk remains high due to their low fixed costs. But uniform filtering requirements dominate at more stringent risk levels, as the much lower unit costs of filtering make up for its larger fixed costs when effort levels are greater. Heat is never a cost-effective option due to its high unit cost, which is consistent with the views of Pollutech (1996). Trading always dominates the uniform treatment requirements, although the cost differences greatly diminish as overall risk is reduced. Trading results in 25 percent lower costs than uniform ballast exchange requirements when Φ=0.1, but it is only 1.6 percent more efficient than uniform filtering requirements when Φ=0.01. The reasons are the same as they were when describing differences between the least cost and trading options – vessels must undertake more uniform actions as the stringency of the environmental goal is increased.

Conclusion

Although emissions cannot be measured or controlled with certainty and not every vessel will actually emit a species, market-based approaches involving tradable permits could be adapted to IAS problems. Such a program would involve trades in probabilities of invasion rather than trades in actual outcomes. Even though risk-based permits are likely to have high transaction costs, they offer the potential to achieve risk reductions at lower cost than uniform technology standards. A model of Great Lakes shipping was developed to evaluated the potential gains that risk-based trading might offer relative to uniform technology regulations for ballast water control.

The simulation results suggest that trading has potential to outperform uniform technology requirements, though the efficiency gains from trading depend on the permitted level of aggregate invasion risk. At less stringent target levels for aggregate invasion risks, i.e., at higher probabilities of invasion in any year, cost savings for trading do emerge. The cost savings stem from the heterogeneity in invasion risks and biosecurity cost structures associated with alternative vessel classes. If vessels are given flexibility to exploit these differences, the decentralized trading of vessel-specific risk permits allows the aggregate risk target to be achieved at lower total cost. However, at more stringent levels, the responses of vessels are limited and potential cost savings from trading are smallest. For these lower risk levels, most vessels adopt filtering in the least cost solution. When it is efficient for a large share of the vessels to use the control same technology, the gains from trading will be small. Thus, despite the heterogeneity of vessels, the findings suggest that a uniform technology can achieve risk reductions and relatively low costs if the right technology is selected. Choosing the low cost technology is key to this finding since the results indicate heat is substantially more costly than the other technologies at all target levels of aggregate invasion risk. It should be noted that the model results reported here are based on the limited information that is currently available about the biosecurity costs of different vessel classes, and better information on the fixed and variable costs of ballast control technologies is warranted.

References

Arrow K.J., and L. Hurwicz. "An Optimality Criterion for Decision-Making under Ignorance." *Uncertainty and Expectations in Economics*. C.F. Carter and J.L. Ford, eds., pp. 1-11. Oxford: Blackwell, 1972.

Aseinova, A.A., "*Clupeonella cultriventris caspia*", Caspian Sea Biodiversity Database, Caspian Environment Programme, http://www.caspianenvironment.org/biodb/eng/main.htm, downloaded March 31, 2003.

Baumol, W.J. and W.E. Oates, *The Theory of Environmental Policy*, Cambridge University Press, New York, 1988.

Baychorov, V.M.. 1980. Reproduction of the Mysid Paramysis lacustris (Crustacea) in the Northern and Southern Zones of Its Introduction. *Hydrobiological Journal, 15(6): 29-34.*

Beavis, B. and M. Walker, "Achieving Environmental Standards with Stochastic Discharges", *Journal of Environmental Economics and Management*, 10, 103-111, 1983.

Chichilnisky, G. "The Economics of Global Environmental Risks." *The International Yearbook of Environmental and Resource Economics 1998/9*. T. Tietenberg and H. Folmer, eds., pp. 235-278. Cheltenham: Edward Elgar, 1998.

Coscarelli, M. and E. Bankard. *Aquatic Nuisance Species Handbook for Government Officials,* Office of the Great Lakes, Michigan Department of Environmental Quality, Lansing, MI, 1999.

Farley, R.B., "Analysis of Overseas Vessel Transits into the Great Lakes through Commercial Shipping Ballast Water and Assessment of Control Options, Phase I and Phase II," unpublished paper (Ann Arbor, MI: University of Michigan Department of Naval Architecture and Marine Engineering, October 1996).

Farley, W.B. "Market Risk Assessment of Catastrophic Risks." *The Risk Analysis Controversy: An Institutional Perspective*. H.C. Kunreuther and E.V. Ley, eds., pp. 195-202. New York: Springer-Verlag, 1982.

Fishburn, P. *Non-Linear Preference and Utility Theory*, Brighton: Wheatsheaf, 1988.

Hahn, R.W., "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders", *Journal of Economic Perspectives*, 3, 95-114, 1989.

Hamouda, O., and R. Rowley. "Ignorance and the Absence of Probabilities." *Uncertainty in Economic Thought*. C. Schmidt, ed., pp. 38-64. Cheltenham: Edward Elgar, 1996.

Hanley, M., J.F. Shogren and B. White. 1997. *Environmental Economics in Theory and Practice*. New York, Oxford University Press.

Heywood, V. (ed). *Global Biodiversity Assessment*. Cambridge: Cambridge University Press, 1995.

Hoag, D.L. and J.S. Hughes-Popp. 1997. Theory and Practice of Pollution Credit Trading in Water Quality Management, *Review of Agricultural Economics*, 19, 252-262, 1997.

Holmes, B. “Day of the Sparrow.” *New Scientist*, June 27 1998, pp. 32-35.

Horan, R.D., J.S. Shortle, and D.G. Abler. 2002. Nutrient Point-Nonpoint Trading in the Susquehanna River Basin, *Water Resources Research*, 38(5): 8-1 – 8-13, 10.1029/2001WR000853.

Horan, R.D. 2001. Cost-Effective and Stochastic Dominance Approaches to Stochastic Pollution Control, *Environmental and Resource Economics*, 18: 373-389.

Katzman, M.T. “Pollution Liability Insurance and Catastrophic Environmental Risk.” *J. Risk and Insur.* 55(March 1988): 75-100.

Katzner, D.W. *Time, Ignorance and Uncertainty in Economic Models*. Ann Arbor: University of Michigan Press, 1998.

Kelsey, D., and J. Quiggin. “Theories of Choice Under Ignorance and Uncertainty. *J. Econ. Surveys.* 6(1992): 133-153.

Lattimore, P., J. Baker, and A. Witte. “The Influence of Probability on Risky Choices: A Parametric Examination.” *J. Econ. Behav. and Org.* 17(May 1992): 377-400.

Lichtenberg, E. and D. Zilberman, “Efficient Regulation of Environmental Health Risks”, *Quarterly Journal of Economics,* 49, 167-168, 1988.

Lichtenberg., E., D. Zilberman and K Bogen, “Regulating Environmental Health Risks Under Uncertainty: Groundwater Contamination in California”, *Journal of Environmental Economics and Management,* 17, 22-34, 1989.

Malik, A.S., D. Letson, and S.R. Crutchfield. 1993. Point/Nonpoint Source Trading of Pollution Abatement: Choosing the Right Trading Ratio, *American Journal of Agricultural Economics*, 75, 959-967.

McGartland, A.M., and W.A. Oates, Marketable Permits for the Prevention of Environmental Deterioration, *Journal of Environmental Economics and Management*, 13, 189-197, 1985.

Michigan Department of Environmental Quality (MDEQ). *Nonindigenous Aquatic Nuisance Species State Management Plan: A Strategy to Confront Their Spread in Michigan*. (Downloaded October 25, 2001).

Mills, E.L., J.H. Leach, J.T. Carlton, and C.L. Secor. 1993. "Exotic Species in the Great Lakes: A History of Biotic Crises and Anthropogenic Introductions." *Journal of Great Lakes Research* 19: 1-54.

Montgomery, W.D., Markets in Licenses and Efficient Pollution Control, *Journal of Economics Theory*, 5, 395-418, 1972.

National Research Council Committee on Ships' Ballast Operations. 1996. *Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water*.

Parker, I.M., D. Simberloff, W.M. Lonsdale, K. Goodell, M. Wonham, M.H. Williamson, B. Von Holle, P.B. Moyle, J.E. Byers, and L. Goldwasser, "Impact: Toward a Framework for Understanding the Ecological Effects of Invaders." *Bio. Invasions* 1 (1999): 3-19.

Perakis, A.N. and Z. Yang. An Evaluation of the Economic Impact of Proposed Non-Indigenous Species Legislation for the St. Lawrence Seaway Using Multi-Attribute Decision Theory, Interim Report to the Michigan Sea Grant Program, May 2001.

Perrings, C. "Environmental Bonds and Environmental Research in Innovative Activities." *Ecol. Econ.* 1(1989): 95-115.

Perrings, C., M. Williamson, and S. Dalmazzone (eds). *The Economics of Biological Invasions*. Cheltenham: Edward Elgar, 2000.

Perrings, C., M. Williamson, E. B. Barbier, D. Delfino, S. Dalmazzone, J. Shogren, P. Simmons, and A. Watkinson. "Biological Invasion Risks and the Public Good: An Economic Perspective." *Conservation Ecology* 6(2002): 1. [online] URL: http://www.consecol.org/vol6/iss1/art1

Peterson, A.T., and D.A.Vieglais. 2001. Predicting Species Invasions Using Ecological Niche Modeling: New Approaches from Bioinformatics Attack a Pressing Problem, *BioScience*, Vol. 51, No. 5, 363-371.

Pezzack, D.S., and S. Corey. 1979. The Life History and Distribution of *Neomysis Americana* (Smith) (Crustacea, Mysidacea) in Passamaquoddy Bay. *Can. J. Zool.* 57:785-793.

Pollutech Environmental Limited, 1996. A Review and Evaluation of Ballast Water Management and Treatment Options to Reduce the Potential for the Introduction of Non-Native Species to the Great Lakes.

Rajagopal, S. G. van der Velde, B.G. P. Paffen, F.W.B. van den Brink, and A. Bij de Vaate. 1999. Life History and Reproductive Biology of the Invasive Amphipod *Corophium Curvispinum* (Crustacea: Amphipoda) in the Lower Rhine. *E. Schweizerbart'sche Verlagsbuchhandlung, D-70176 Stuttgart. Arch. Hydrobiol.* 144, 3, 305-325

Reeves, E. 1999. *Exotic Policy: An IJC White Paper on Policies for the Prevention of the Invasion of the Great Lakes by Exotic Organisms*. 1999 Great Lakes Water Quality Forum, Milwaukee, WI.

Ricciardi, A., and J.B. Rasmussen. 1998. Predicting the Identity and Impact of Future Biological Invaders: A Priority for Aquatic Resource Management. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 1759-1765.

Rigby, G. and A.H. Taylor. 2001. Ballast Water Report Series No. 13. Ballast Water Treatment to Minimise the Risks of Introducing Nonindigenous Marine Organisms into Australian Ports. Prepared for the Department of Agriculture Fisheries and Forestry – Australia.

Savage, L.J. *The Foundations of Statistics*. New York: Wiley, 1954.

Shackle, G.L.S. *Decision, Order and Time in Human Affairs*. Cambridge: Cambridge University Press, 1969.

Shortle, J.S and J. W. Dunn. 1986. "The Relative Efficiency of Agricultural Source Water Pollution Control Policies." *Amer. J. Agr. Econ.* 68 (August 1986): 668-677.

Shortle, J.S. 1990. The Allocative Efficiency Implications of Water Pollution Abatement Control Cost Comparisons, *Water Resources Research*, 26, 793-797.

Shortle, J.S., and D.G. Abler. 1997. Nonpoint Pollution, in *The International Yearbook of Environmental and Resource Economics 1997/98*, edited by H. Folmer and T. Tietenberg, Edward Elgar, Cheltenham, UK, 1997.

Simpson, R.D., R.A. Sedjo, and J.W. Reid. "Valuing Biodiversity for Use in Pharmaceutical Research." *J. Polit. Econ.* 104 (February 1996): 163-185.

Starmer, C., and R. Sugden. "Violations of the Independence Axiom in Common Ratio Problems: An Experimental Test of Some Competing Hypotheses." *Ann. Oper. Res.* 19(1989): 79-102.

Tietenberg, T.H., Tradeable Permits for Pollution Control when Emission Location Matters: What have We Learned? *Environmental and Resource Economics*, 5, 95-113, 1995.

Turvey, R. On Divergences Between Social Cost and Private Cost, *Economica* **30**, 309-323, 1963.

Tversky, A., and D. Kahneman. "Advances in Prospect Theory: Cumulative Representation of Uncertainty." *J. Risk Uncertainty.* 5(October 1992): 297-323

U.S. EPA. 2001. Aquatic Nuisance Species in Ballast Water Discharges: Issues and Options. Draft Report for Public Comment for Office of Water, Office of Wetlands, Oceans and Watersheds, Office of Wastewater Management, Washington, DC.

Vickers, D. *Money Capital in the Theory of the Firm.* Cambridge: Cambridge University Press, 1987.

Williamson, M. *Biological Invasions*. London: Chapman and Hall, 1996.

Table 1. Effectiveness of Various Ballast Water Management Technologies for Great Lakes Target Species

Target Species	Control Technology		
	Ballast Exchange	Heating	Filtration
Corophium spp.	Not generally effective at killing organisms (Rigby and Taylor 2001). Somewhat effective at removing individual organisms from the tanks as the exchange occurs. We assume efficiency equals the proportion of exchange that occurs.	*Corophium curvispinum* have been known to naturally occur in warm lakes up to 31^{o} C (Rajagopal et al. 1999), although this may not be the upper bound on survival. Mortality rates will depend on the ballast water temperature achieved, the time to achieve it, and the duration of heating. Temperatures in excess of 40^{o}C are hard to achieve and maintain in colder waters such as the Northern Atlantic. We assume 90% efficiency for 40^{o}C ($x_h = 1$) and 50% efficiency for 35^{o}C ($x_h = 0.5$).	*Corophium* are marsupial-like amphipods that carry their young in pouches until the eggs hatch. There are many related species. For *Corophium curvispinum*, juveniles are 550μm in length (Rajagopal et al. 1999) but possibly narrow enough to fit through mesh. Juveniles are up to 1.8 mm and adults average 3.75 mm (Rajagopal et al. 1999). Rigby and Taylor (2001) report removal efficiency of 50 μm to 25 μm filters to be from 80% for small rotifers (rotifers usually range in length from 1mm to 250 mm) and 95% for bivalve vetigers. Given the size of juveniles, we assume 60% efficiency for the 50μm filter ($x_f = 0.5$) and 95% for 25μm filter ($x_f = 1$).
Mysids		The species *Paramysis lacustris* have been known to survive *in situ* in temperatures up to 28^{o} C (Baychorov 1980), although this may not be the upper bound for survival. We assume 95% efficiency for 40^{o}C ($x_h = 1$) and 60% efficiency for 35^{o}C ($x_h = 0.5$).	Mysids are marsupial-like shrimp that carry their young in pouches until the juvenile stage. There are many related species. For the species *Paramysis lacustris*, adult females range in size from 10-14mm (Baychorov 1980). Sizes of newly released juveniles were not reported, but for the related species *Neomysis Americana* this size averaged 710 μm (Pezzack and Corey 1979). Given that mysids are generally larger than *corophium* and that egg deposition is not a concern for mysids, we use slightly larger removal efficiencies than for *corophium*: 80% for $x_f = 0.5$ and 98% for $x_f = 1$.

Clupeonella caspia.		The species *clupeonella cultriventris caspia* naturally occurs in temperatures up to 26^o C (Aseinova 2003), although this may not be the upper bound for survival. We assume 99% efficiency for 40^{o}C ($x_h = 1$) and 90% efficiency for 35^{o}C ($x_h = 0.5$).	For *clupeonella cultriventris caspia*, eggs are 1mm, larvae are 1.3-1.8 mm, and fingerlings are 50-55mm. Adults average 7.8 cm – much too large to fit through any filter. However, population structures are weighted heavily by newer recruits (Aseinova 2003). Sizes of these younger fish are similar to rotifers and small copepods. We adopt Ribgy and Taylor's (2001) reported removal efficiencies for copepods: assume 95% effectiveness for a 100µm filter ($x_f = 0.1$) and 99% effectiveness for the 25µm filter ($x_f = 1$).

Table 2. Costs of Various Ballast Water Management Technologies

Ballast Capacity (m^3)	Control Technology					
	Ballast Exchange (with $x_b = 0.75$)		Heating (with $x_h = 1$)		Filtration (with $x_f = 1$)	
	Operating Costs (U.S. cents/m^3)	Fixed Costs (U.S. cents/m^3)	Operating Costs (U.S. cents/m^3)	Fixed Costs (U.S. cents/m^3)	Operating Costs (U.S. cents/m^3)	Fixed Costs (U.S. cents/m^3)
12,000	2.814	2.238	2.684	0.432	0.18	19.05
60,000	2.244	0.54	3.355	0.54	0.48	6.564

Table 3. Simulation results

Scenario	**Annual Costs (millions US$)**	**Proportion of Total Costs in:**		**Probability of invasion**			**Risk Heterogeneity Across Vessels**[a]
		Ballast Exchange	**Filtering**	***Corophium spp.***	**Mysids**	***Clupeonella caspia.***	
Base Case (no biosecurity)	0			0.28	0.28	0.28	----
Case I: $\Phi_s \leq 0.1 \quad \forall s$							
Least Cost	4.72	0.37	0.63	0.10	.10	0.04	1.73
Trading	6.11	0.21	0.79	0.10	0.08	.022	1.25
Uniform filtering requirement	7.81	0	1.0	0.10	0.05	0.008	0.82
Uniform heat requirement	42.57	0	0	0.10	0.08	0.02	0.82
Uniform ballast exchange requirement	7.64	1.0	0	0.10	0.10	0.10	0.82
Case II: $\Phi_s \leq 0.05 \quad \forall s$							
Least Cost	6.18	0.17	0.83	0.05	0.05	0.02	1.99
Trading	7.45	0.20	0.80	0.05	0.03	0.008	1.51
Uniform filtering requirement	7.99	0	1.0	0.05	0.02	0.005	0.82
Uniform heat requirement	54.96	0	0	0.05	0.03	0.007	0.82
Uniform ballast exchange requirement	10.37	1.0	0	0.05	0.05	0.05	0.82
Case III: $\Phi_s \leq 0.01 \quad \forall s$							
Least Cost	7.54	0.14	0.86	0.01	0.01	0.006	2.87
Trading	8.00	0.20	0.80	0.01	0.005	0.003	2.18
Uniform filtering requirement	8.13	0	1.0	0.01	0.004	0.003	0.82
Uniform heat requirement	64.63	0	0	0.01	0.00	0.00	0.82
Uniform ballast exchange requirement	12.65	1.0	0	0.01	0.01	0.01	0.82

[a] This is measured by the coefficient of variation in q_{is} across vessels, where *s* is the species for which the probabilistic constraint binds.