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Tradeable risk permits to prevent future introductions of invasive alien species into the Great Lakes

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Abstract

Commercial shipping has been implicated in over 60% of new introductions of invasive alien species (IAS) in the Great Lakes since 1960, with ballast water being the primary pathway. Recent policies have shifted the focus from postinvasion controls to prevention, with the regulation of oceanic ballast exchange as the primary approach. But this approach is not very effective, and it is often unsafe. We investigate whether an IAS tradeable permit program could provide an efficient alternative, keeping in mind that: (1) not every vessel will actually emit a species, yet ex ante each vessel is a potential emitter; (2) biological emissions are highly stochastic and essentially unobservable given current monitoring technologies. Theoretical issues in the design of a trading program are considered. We then compare the cost-effectiveness of trading versus command and control to reduce the likelihood of invasion by three classes of Ponto–Caspian species that are considered potential invaders capable of causing economic damage in the Great Lakes.

Keywords: Aquatic nuisance species; Ballast water; Uncertainty; Risk management; Permit trading

1. 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, 1998; U.S. EPA, 2001). Without natural predators, parasites, and/or pathogens to help control population growth, IAS frequently outcompete or prey on native species. Some can 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) and result in significant economic impacts (Perrings et al., 2000).

In this paper, we treat IAS introductions by commercial shipping vessels as a form of biological

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pollution, and we investigate the potential for developing a permit trading system to prevent new introductions in the Great Lakes. IAS have had a significant impact on the Great Lakes. At least 145 IAS have been introduced into the Great Lakes since the 1830s, with one-third being introduced during the past 30 years—likely in response to increased shipping in the St. Lawrence Seaway (MDEQ, 2001; Great Lakes Commission, 2000). Only about 10% 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, one estimate suggests that zebra mussels could cause five billion dollars in damages over the next 10 years (MDEQ, 2001).

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., integrated pest management [IPM]), or adaptation. Historically, efforts have focused on eradication and postinvasion control (Lupi et al., 2003), 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.[2] 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).[3] 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 2000 m, so that ballast salinity levels are raised to 30 ppt (ocean salinity levels range between 34 to 36 ppt). 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).[4]

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.[5] Second, ballast exchange typically does not result in a 100% 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

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

[3] 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.

[4] 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 typically do not occur (Reeves, 1999).

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

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 regulations imposing uniform technology standards would be less cost-effective than performance-based approaches that allow each vessel to make individualized choices. Alternatively, 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 of controlling various forms of air and water pollution in the United States 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).[6] 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. This would be somewhat analogous to existing point–nonpoint trading programs to improve water quality, although in the present context, an emissions estimate is more accurately described as the probability of a species introduction by the vessel. California has implemented a permit program that could be viewed as a precursor to the one we examine. Vessels are issued permits based on ballast exchange, but vessels are free to adopt alternative technologies that achieve similar outcomes in terms of risk reduction (Karaminas et al., 2000). The only thing missing is the ability to trade the permits.

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 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.

2. A model of IAS invasions

The model we adopt builds on that of Horan et al. (2002a). 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

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[6] We thank a reviewer for pointing out that there is one notable difference between vessels and more traditional examples of nonpoint sources, such as agriculture. Specifically, agricultural lands (and most nonpoint sources) are fixed in space whereas vessels are not. To some degree, vessels are more like cars and trucks, which some consider to be nonpoint sources. Mobility might make monitoring and enforcement more difficult. However, vessels are a fixed entity and can be fairly easy to track once they are in the vicinity of a port—particularly a closed area such as the Great Lakes.

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 may 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 $\Pr_s(\text{survival}|\, e_{is},\, x_i,\, l)$, 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 $q_{is}(x_i, b_i, l) = \sum_{e_{is}} \Pr_s(\text{survival}|e_{is}, x_i, l)p_{is}(e_{is}|x_i, b_i)$. 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 are 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

$$\begin{aligned} P_s(x_1,\ldots,x_n) &= P_s(Z_s \geq 1) = 1 - P(Z_s = 0) \\ &= 1 - \prod_{i=1}^{n} (1 - q_{is}(x_i, b_i, l)) \end{aligned} \tag{1}$$

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 sth species are $D_s(\gamma_s)$, where γ_s is a random variable reflecting uncertain damage costs.[7] 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

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[7] 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.

value of θ_s, by $P_s(x_1,...,x_n|\theta_s)$. Defining E as the expectations operator over all stochastic variables, expected damages are

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

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

Ex ante efficient or first-best biosecurity measures minimize the expected social cost of biological pollution and its control[8]

$$\underset{x_{ij}\forall i,j}{\text{Min}} \sum_{i=1}^{n} c_i(x_i) + E\{D(x_1,\ldots,x_n)\}. \quad (3)$$

The necessary conditions for an interior solution can be written as

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

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 $\theta_s \in \emptyset$. Further interpretations of (4) are provided by Horan et al. (2002a).

4. A model of trading

We now consider a tradeable permit system as a mechanism for encouraging prevention of biological emissions. We begin by focusing on a first-best system. Ultimately, we find that the first-best system would be too complex to implement for a number of reasons, including the requirement that an excessive number of different permit types must be traded at vessel-specific rates, and that information would be required on all potential invaders, the likelihood of invasion, and the potential expected damages from invasion. But working through the first-best case is useful because it provides insight into the issues that must be addressed in the development of a more practicable second-best system, which we describe in the following section and which involves a single type of permit and focuses on a few potential invaders as target species.

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 (Malik et al., 1993; Horan et al., 2002b), which are calculated by a model that links on-site management practices and farm

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[8] 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 nonconvexities. 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. (2002a) illustrate that making decisions in this fashion can be equivalent to using the expected utility model with subjective weights applied to the reference point.

characteristics with expected changes in water quality.[9] 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 (Kolar and Lodge, 2002; 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. Note that our model focuses on risks to a particular region (e.g., the Great Lakes) or port of entry, and so we are only considering within-region risk trading (as opposed to a cross-port trading system).[10] In this context, a vessel's port of origin is only important via its influence on the risk level, and it can be considered a choice variable in the vector x_i. Our model is timeless so we do not address issues related to the duration of the permit. However, it is worth noting that vessels pose risk the entire time they are in the region, and so their permit should reflect this.

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,

$$\min_{x_i, r_{is}} \quad c_i(x_i) + \sum_s u_s\left(r_{is} - r_{is0}\right) \qquad \text{s.t.} \quad q_{is} \leq r_{is}. \tag{5}$$

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

$$\min_{x_i} \quad c_i(x_i) + \sum_s u_s\left(q_{is}(x_i) - r_{is0}\right). \tag{6}$$

The resulting first-order conditions are

$$\frac{\partial c_i}{\partial x_{ij}} = -\sum_s u_s \frac{\partial q_{is}}{\partial x_{ij}} \quad \forall i,j. \tag{7}$$

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

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

where the starred (*) terms on the right-hand side (RHS) of Eq. (8) indicate that these relations are evaluated at their optimal levels. Condition (8) represents a series of $n \times m$ nonlinear equations (with the nonlinearities necessarily arising due to the construction of P_s) in S unknowns—that is, S policy tools. If $n \times m > S$, 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 $n \times m < S$, 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 Eq. (8)

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

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

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

where $P_{s,-i} = 1 - \Pi_{k \neq i}(1 - q_{ks}(\bullet|\theta_s))$ is the aggregate probability (conditional on θ_s) that species s

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[9] 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-Fortan (HSPF), and the Generalized Watershed Loading Function (GWLF).

[10] One could imagine cross-port permit trading, which would involve trading risks across regions. Efficiency in this case would be increased by applying trading ratios that define the appropriate substitutability of risks between regions (see Horan et al., 2002b and Malik et al., 1993 for discussions of trading ratios in point–nonpoint permit trading programs). Otherwise, risks would be traded on a 1:1 basis which would reduce efficiency if the risks were imperfect substitutes.

will invade from any vessel other than vessel i. The two terms on the RHS of Eq. (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, 1995). 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 Eq. (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 be first-best (i.e., satisfy Eq. (4)) when $\theta_s \notin \emptyset$ because it does not provide firms with incentives to consider all of the impacts of their choices on damages.

A first-best trading program when $\theta_s \notin \emptyset$ 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 separate permits being traded at $n \times m$ 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.

5. Second-best management

Consider a market in 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., 2002a), 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

$$P_s(x_1, \ldots, x_n) \le \Phi_s \quad \forall s \in \hat{S} \tag{11}$$

where $0 \le \Phi_s \le 1$ and $\hat{S}$ (with $\hat{S} \subseteq S$) represents a set of target species upon which controls are based. This focus on target species is an approach that has been formally adopted by the Australian Ballast Water Management Council (Rigby and Taylor, 2001). The "safety-first" approach implied by Eq. (11), 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).[11]

A second-best allocation of biosecurity measures minimizes the expected cost of biological pollution control (TC) subject to Eq. (11) and also subject to vessel responses to the permit system.[12] There are two ways to determine the number of permits that minimize TC, subject to Eq. (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.[13] 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

$$\underset{u}{\text{Min}}\ \text{TC} = \sum_{i-1}^{n} c_i(x_i(u))$$
$$\text{s.t. } P_s(x_1(u),\ldots,x_n(u)) \le \Phi_s \quad \forall s \in \hat{S} \tag{12}$$

If the permit system is not denominated according to different species (which would avoid administrative difficulties if the number of target species was large), then in the trading solution, it will not be possible to satisfy each constraint in Eq. (12) as an equality. The first-order conditions for the cost minimization problem (12) are

$$\sum_i \sum_j \frac{\partial c_i}{\partial x_{ij}} \frac{\partial x_{ij}}{\partial_{\mathrm{u}}} = -\sum_s \sum_i \sum_j \lambda_s \frac{\partial P_s}{\partial x_{ij}} \times \frac{\partial x_{ij}}{\partial_{\mathrm{u}}} \tag{13}$$

along with the constraint (11), where λ_s is the shadow value of the sth constraint. Using the vessels' first-order conditions, Eq. (13) can be solved for the optimal permit price

$$u = \frac{\sum_s \sum_i \sum_j \lambda_s^* \frac{\partial P_s^*}{\partial x_{ij}} \kappa_{ij}^*}{\sum_i \sum_j \frac{\partial q_i^*}{\partial x_{ij}} \kappa_{ij}^*} \tag{14}$$

where $\kappa_{ij}^* = (\partial x_{ij}^* / \partial u) / \sum_i \sum_j (\partial x_{ij}^* / \partial u)$, and the superscript (*) indicates that all variables are evaluated at their optimal values as the solution to Eq. (12).

Interpreting κ_{ij}^* as a weight (since $\sum_i \sum_j \kappa_{ij}^* = 1$), 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 Eq. (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.

6. An application to Great Lakes shipping

Each year, approximately 200–300 transoceanic vessels enter the Great Lakes and account for 400–600 round trips in and out of the region. More than 70% of entering vessels are engaged in the 'triangle trade', taking grain from the Great Lakes to the

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[11] 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.

[12] Another second-best issue, which we do not address, is that of using the permit program for protectionist purposes. This could be an issue because permit programs (and other regulatory measures) alter the relative cost of trade across regions, and could therefore be used to restrict imports in some locales. See Margolis and Shogren (2004) for a discussion of these issues.

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

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.

We use official statistics on a subset of 315 transoceanic vessels that travel the St. Lawrence Seaway (U.S. Army Corp of Engineers, 2002), representing the majority of Seaway vessels, in order to develop 31 “classes” of vessels based on vessels’ deadweight tonnage (DWT). Costs and probabilities are then aggregated within each class using a micro-parameter approach (Just and Antle, 1990). 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 ith 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 formally 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% of Great Lakes invaders between 1985 and 2000 (Reid and Orlova, 2002). The Ponto–Caspian species *Corophium* spp. (a small amphipod), Mysids (a small shrimp), and *Clupeonella caspia* (a small fish) have been identified as likely invaders capable of causing extensive damage (Kolar and Lodge, 2002; Ricciardi and Rasmussen, 1998).

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}. In our model, 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 β_s. In the absence of biosecurity efforts, $\beta_s\alpha_{is}b_i$ 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 $\phi_{fs}(x_{if})$ (with $x_{if}\in[0,1]$ and $\phi_{fs}(0)=0$, $\phi_{fs}(1)=\phi_{fs}^U$ where ϕ_{fs}^U is an upper bound on ϕ_{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. Similarly, heat must be applied at a high enough temperature for a long enough period of time to kill undesired organisms, 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

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 °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 °C are hard to achieve and maintain in colder waters such as the Northern Atlantic. We assume 90% efficiency for 40 °C (x_h=1) and 50% efficiency for 35 °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 550 μm 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 1 to 250 mm) and 95% for bivalve vetigers. Given the size of juveniles, we assume 60% efficiency for the 50 μm filter ($x_f=0.5$) and 95% for 25 μm filter ($x_f=1$).
Mysids		The species *Paramysis lacustris* have been known to survive in situ in temperatures up to 28 °C (Baychorov, 1980), although this may not be the upper bound for survival. We assume 95% efficiency for 40 °C (x_h=1) and 60% efficiency for 35 °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 to 14 mm (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 °C (Aseinova, 2003), although this may not be the upper bound for survival. We assume 99% efficiency for 40 °C (x_h=1) and 90% efficiency for 35 °C (x_h=0.5).	For *Clupeonella cultriventris caspia*, eggs are 1 mm, larvae are 1.3–1.8 mm, and fingerlings are 50–55 mm. 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 100 μm filter ($x_f=0.1$) and 99% effectiveness for the 25 μm filter ($x_f=1$).

Table adapted from Horan and Lupi, interim report to Michigan Sea Grant College Program, 2003.

Table 2
Costs of various ballast water management technologies[a]

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

[a] Table adapted from Rigby and Taylor (2001).

species s by $\phi_{js}(x_{ij})$ (with $x_{ij}\in[0,1]$ and $\phi_{js}(0)=0$, $\phi_{js}(1)=\phi_{js}^U$, where ϕ_{js}^U is an upper bound on ϕ_{js}).[14]

Given this specification, the probability that species s invades due to the activities of vessel i is given by $q_{is}=\beta_s[1-\phi_{Bs}(x_{iB})][1-\phi_{hs}(x_{ih})][1-\phi_{fs}(x_{if})]k_{is}$, where the indices B and h represent ballast exchange and heat, respectively. The function $\phi_{js}(x_{ij})=\mu_{ij}x_{ij}^{\delta_{js}}$ ($j=f,B,h$), where μ_{ij} and δ_{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). The parameter β_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 10% chance of establishing a viable population in the new ecosystem. The parameter α_s is calibrated to ensure that each species has a moderate chance of invasion in any particular year when there are no policies or controls in place. Specifically, each species has a 10% chance of invasion in any given year in the unregulated base case. This corresponds to a 65% chance of invasion over the next decade, which is consistent with the view that scientists believe an invasion by each of these species is somewhat likely in the near future (Ricciardi and Rasmussen, 1998; Kolar and Lodge, 2002). Note that although α_s and β_s are the same for each vessel, q_{is} varies considerably by vessel since this value also depends on the vessel's size.

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, $w_{ij}=\gamma_{ij}b_i^{\rho_{ij}}$. There is also a fixed capital cost associated with the use of some technologies. Fixed costs (Table 2) also depend on vessel size, so that $F_{ij}=\Gamma_{ij}b_i^{\sigma_{ij}}$.[15]

With multiple technologies and associated fixed costs, determining optimal allocations of control efforts requires that we solve a constrained, mixed-integer nonlinear programming 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. With 31 vessel classes that can each choose up to three technologies (and also the option to not adopt each), this amounts 8^{31} possible combinations. Fortunately, most 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 due to the high fixed costs of adoption. 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

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[14] 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 misrepresent their actual effort levels.

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

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. Using this algorithm to eliminate such dominated permutations, the bulk of possibilities are ruled out. This enables us to solve and compare results from a manageable subset of permutations.

7. 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 1–1 risk permit trading market (second best), and various uniform technological regulations. Costs are also presented graphically in Fig. 1 for various levels of risk Φ. Costs are expressed as an index with the base being industry costs in the least cost outcome when Φ=0.05 (the least stringent case). A value of 150, for example, would indicate that costs are 50% larger than base costs.

First, consider the least cost scenario. The aggregate mix of adopted technologies depends on the value of Φ. 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. Heating's high unit costs prevent it from being a preferred option by any vessel for any value of Φ.

Table 3
Simulation results

Scenario	Annual Costs[a]	Proportion of total costs in:		Probability of invasion			Risk heterogeneity across vessels[b]
		Ballast exchange	Filtration	*Corophium* spp.	Mysids	*Clupeonella caspia*	
Base case (no biosecurity)	0			0.1	0.1	0.1	–
Case I: $\Phi_s \leq 0.05\ \forall s$							
Least cost	100	0.41	0.59	0.05	0.05	0.02	1.31
Trading	138	0.65	0.35	0.05	0.047	0.016	0.98
Uniform filtration requirement	234	0	1.0	0.05	0.027	0.004	0.64
Uniform heat requirement	962	0	0	0.05	0.04	0.01	0.64
Uniform ballast exchange requirement	143	1.0	0	0.05	0.05	0.05	0.64
Case II: $\Phi_s \leq 0.01\ \forall s$							
Least cost	212	0.08	0.92	0.01	0.01	0.004	1.98
Trading	220	0.09	0.91	0.01	0.008	0.003	1.62
Uniform filtration requirement	244	0	1.0	0.01	0.004	0.001	0.64
Uniform heat requirement	2014	0	0	0.01	0.005	0.001	0.64
Uniform ballast exchange requirement	337	1.0	0	0.01	0.01	0.01	0.64
Case III: $\Phi_s \leq 0.005\ \forall s$							
Least cost	221	0.09	0.91	0.005	0.005	0.002	2.28
Trading	235	0.09	0.91	0.005	0.003	0.001	1.74
Uniform filtration requirement	246	0	1.0	0.005	0.002	0.001	0.64
Uniform heat requirement	2146	0	0	0.005	0.001	0.001	0.64
Uniform ballast exchange requirement	364	1.0	0	0.005	0.005	0.005	0.64

[a] Costs are expressed as a percentage of costs in the least cost outcome under case I.

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

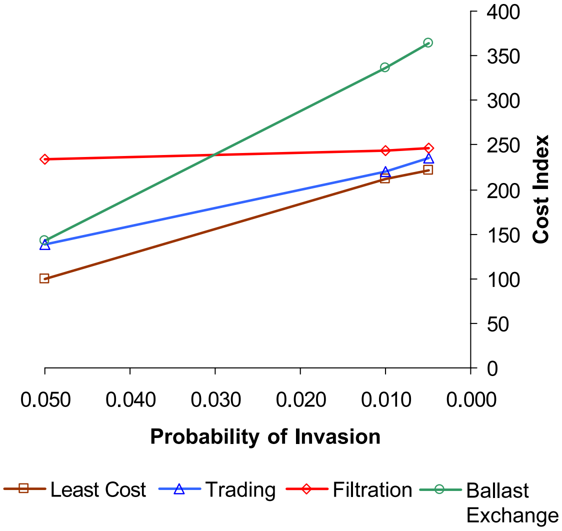

Fig. 1. Comparing cost curves by regulatory approach.

Because vessels optimally utilize different technologies to varying degrees of effectiveness in the least cost outcome, we find that heterogeneity in risk across vessels is optimal although 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 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. At lower levels of risk, larger vessels apply fairly uniformly high effort levels to filtration technology while smaller vessels apply fairly uniformly low effort levels to the less-effective ballast exchange technology. This effort mix creates some heterogeneity across technologies but not within a particular technology class. In order to achieve more stringent goals, some small vessels optimally increase their ballast exchange control efforts while others optimally incur the fixed costs of a switch to filtration. Filtration is more effective than ballast exchange at a given level of effort, and so the switch to filtration coincides with a downward jump in the risk of an invasion. In turn, the downward jump allows some larger vessels to reduce their efforts. The result is greater heterogeneity in risk across vessels that adopt filtration, which constitutes the majority of vessels. One would expect that the distribution of effort again becomes modal and risk heterogeneity reduced as $\Phi \rightarrow 0$ and all vessels adopt filtration.

Now consider the trading scenario. The relative performance of the trading system depends on the overall risk level, as is clearly evident in Fig. 1. When Φ=0.05, control costs are 38% larger under trading than in the least cost allocation, while there is only a 14% difference when Φ=0.005. The inefficiencies of trading are diminished as Φ becomes smaller because there are fewer technological/behavioral options as Φ is reduced. Under either the least cost or trading scenarios, most vessels adopt filtration when Φ is set at low levels and they increase their effort levels in this technology as Φ is reduced. But vessels can only increase their effort levels so much before they hit an upper bound on the effectiveness of the technology (i.e., ϕ_{if}^{U}). 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 cost differences that could otherwise lead to increased savings. Consequently, the least cost and trading allocations become more similar when the aggregate risk goal is lowered.

Where inefficiencies do arise under a trading program, trading results in higher costs for two reasons. First, permits are not defined for particular species and so vessels do not have incentives to differentially consider how their choices affect the likelihood of invasion by each species. The result is overcontrol of Mysids and *C. caspia* relative to the least cost outcome.

The trading program's second and perhaps its more important source of inefficiency is that 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. 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.

Finally, consider the results of a uniform technological requirement designed to achieve the desired level of risk. Heat is never a cost-effective option due to its high unit cost, which is consistent with the views of Pollutech (1996). Due to their relatively low fixed costs, uniform ballast exchange requirements are less costly than uniform filtering requirements when the overall level of risk remains high. 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.

Trading always dominates the uniform treatment requirements, although the cost differences depend largely on the technology to be mandated and also on the overall risk level Φ. When $\Phi=0.05$, a uniform filtration requirement is 70% more costly than trading because the majority of vessels in a trading equilibrium would have taken advantage of the low fixed costs of ballast exchange. But with most vessels involved in ballast exchange, trading is only about 4% more efficient than the uniform ballast exchange requirement when $\Phi=0.05$. If trading involves greater transactions costs, then the uniform ballast exchange requirement may make more sense in this situation. But this result changes as Φ is reduced below a value of 0.05. At this point, it becomes more cost-effective for some vessels to incur the high fixed costs of adopting filtration in return for lower variable costs and greater effectiveness, which also implies there are gains from reallocating risk reductions to vessels that have adopted filtration. These gains grow as Φ is reduced. When $\Phi=0.005$, a uniform ballast exchange requirement is 55% more costly than trading because at such low risk levels, the majority of vessels in a trading equilibrium would have incurred the fixed costs of filtration to take advantage of its smaller unit costs. But the efficiencies of trading over the uniform filtration requirement are diminished as Φ becomes smaller because there are fewer technological/behavioral options as Φ is reduced. Indeed, most vessels adopt filtration—and many apply maximum effort to this technology—when $\Phi=0.005$. Trading is therefore only about 5% more efficient than the uniform filtration requirement in this case, and so the uniform filtration requirement may actually be a better choice if trading involves relatively larger transactions costs.

The real gains from trade arise at intermediate aggregate risk levels (i.e., $0.005<\Phi<0.05$), where a significant number of vessels would optimally adopt filtration while applying less than maximum effort to this technology. The gains are seen visually in Fig. 1 by the vertical difference between the trading cost curve and the cost curves associated with either of the uniform technology requirements. The greatest gains occur at the intersection of the two uniform technology requirement cost curves—where filtration begins to dominate ballast exchange. This illustrates that when the aggregate risk level allows for a good mix of technologies and also variation in the effort levels applied to these technologies, there is more room for vessels to exploit cost differences in ways that could increase overall cost savings.

8. Conclusion

Although emissions cannot be measured or controlled with certainty and not every vessel will actually emit a species, market-based approaches involving tradeable permits could be adapted to IAS problems. Such a program would involve trades in probabilities of invasion rather than trades in actual outcomes. Although 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 evaluate 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, although the efficiency gains from trading depend on the permitted level of aggregate invasion risk. At intermediate target levels for aggregate invasion risks, 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 filtration in the least cost solution. When it is efficient for a large share of the vessels to use the same control 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. It should be noted that the model results reported here are based on the limited information that is currently available about invasion risks and the biosecurity costs of different vessel classes. Better economic understanding of the fixed and variable costs as well as better information on species-specific invasion risks and the control effectiveness of alternative ballast control technologies is warranted.

Finally, although the target species approach is useful for determining cost-effective outcomes, it would be better if information on potential damage costs could be used to determine economically desirable invasion risk levels. This information could be used to decide whether any control is worth the cost. Indeed, the costs incurred may not prevent an invasion but rather may only avoid the inevitable. For instance, even at an annual invasion risk of 1%, the risk of invasion over the next decade is 10%, and it climbs to 18% within two decades.

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References

Aseinova, A.A., 2003. *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., Oates, W.E., 1988. The Theory of Environmental Policy. Cambridge University Press, New York.

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., Walker, M., 1983. Achieving environmental standards with stochastic discharges. Journal of Environmental Economics and Management 10, 103–111.

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

Farley, R.B., 1996. 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).

Great Lakes Commission, 2000. Ballast Management for the Prevention and Control of Aquatic Nuisance Species. Great Lakes Commission Resolutions, http://www.glc.org/about/resolutions/ballast.htm, May 25, 2000.

Hahn, R.W., 1989. Economic prescriptions for environmental problems: how the patient followed the doctor's orders. Journal of Economic Perspectives 3, 95–114.

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

Holmes, B., 1998. Day of the sparrow. New Scientist, 32–35. (June 27).

Horan, R.D., Perrings, C., Lupi, F., Bulte, E., 2002a. Biological pollution prevention strategies under ignorance: the case of invasive species. American Journal of Agricultural Economics 84, 1303–1310.

Horan, R.D., Shortle, J.S., Abler, D.G., 2002b. Nutrient point–nonpoint trading in the Susquehanna River Basin. Water Resources Research 38 (5), 8-1–8-13.

Just, R., Antle, J., 1990. Interactions between agricultural and environmental policies. American Economic Review 80, 197–202.

Karaminas, L., Ocakli, H.H., Mazdon, K.C., Westlake, P.C., 2000. Ballast Water Management. LR Technical Association Paper no. 1 Session 2000–2001. Lloyd's Register of Shipping, London.

Kolar, C.S., Lodge, D.M., 2002. Ecological predictions and risk assessments for alien species. Science 298, 1233–1236.

Lichtenberg, E., Zilberman, D., 1988. Efficient regulation of environmental health risks. Quarterly Journal of Economics 49, 167–168.

Lichtenberg, E., Zilberman, D., Bogen, K., 1989. Regulating environmental health risks under uncertainty: groundwater contamination in California. Journal of Environmental Economics and Management 17, 22–34.

Lupi, F., Hoehn, J., Christie, G., 2003. Using an economic model of recreational fishing to evaluate benefits of sea lamprey (*Petromyzon marinus*) control. Journal of Great Lakes Research 29, 742–754.

Malik, A.S., Letson, D., Crutchfield, S.R., 1993. Point/nonpoint source trading of pollution abatement: choosing the right trading ratio. American Journal of Agricultural Economics 75, 959–967.

Margolis, M., Shogren, J.F., 2004. How trade policies affect invasive species control. Ecological Economics 52, 305–313 (this issue).

McGartland, A.M., Oates, W.A., 1985. Marketable permits for the prevention of environmental deterioration. Journal of Environmental Economics and Management 13, 189–197.

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., Leach, J.H., Carlton, J.T., Secor, C.L., 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., 1972. Markets in licenses and efficient pollution control. Journal of Economic Theory 5, 395–418.

National Research Council Committee on Ships' Ballast Operations, 1996. Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water. National Academies Press, Washington, D.C.

Perakis, A.N. and Yang, Z., 2001. 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., Williamson, M., Dalmazzone, S. (Eds.), 2000. The Economics of Biological Invasions. Edward Elgar, Cheltenham.

Perrings, C., Williamson, M., Barbier, E.B., Delfino, D., Dalmazzone, S., Shogren, J., Simmons, P., Watkinson, A., 2002. Biological invasion risks and the public good: an economic perspective. Conservation Ecology 6 (1):1, 1–7. http://www.consecol.org/vol6/iss1/art1.

Peterson, A.T., Vieglais, D.A., 2001. Predicting species invasions using ecological niche modeling: new approaches from bioinformatics attack a pressing problem. BioScience 51 (5), 363–371.

Pezzack, D.S., Corey, S., 1979. The life history and distribution of *Neomysis Americana* (Smith) (Crustacea, Mysidacea) in Passamaquoddy Bay. Canadian Journal of Zoology 57, 785–793.

Pollutech Environmental, 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., van der Velde, G., Paffen, B.G.P., van den Brink, F.W.B., Bij de Vaate, A., 1999. Life history and reproductive biology of the invasive amphipod *Corophium curvispinum* (Crustacea: Amphipoda) in the Lower Rhine. Archiv für Hydrobiologie 144, 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. Great Lakes Water Quality Forum, Milwaukee, WI.

Reid, D.F., Orlova, M.I., 2002. Geological and evolutionary underpinnings for the success of Ponto–Caspian species invasions in the Baltic Sea and North American Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 59, 1144–1158.

Ricciardi, A., Rasmussen, J.B., 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 Taylor, A.H., 2001. Ballast Water Treatment to Minimize the Risks of Introducing Nonindigenous Marine Organisms into Australian Ports. Ballast Water Report Series No. 13. Department of Agriculture Fisheries and Forestry–Australia.

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

Shortle, J.S., Dunn, J.W., 1986. The relative efficiency of agricultural source water pollution control policies. American Journal of Agricultural Economics 68, 668–677.

Shortle, J.S., Abler, D.G., 1997. Nonpoint pollution. In: Folmer, H., Tietenberg, T. (Eds.), The International Yearbook of Environmental and Resource Economics 1997/98. Edward Elgar, Cheltenham, UK.

Tietenberg, T.H., 1995. Tradeable permits for pollution control when emission location matters: what have we learned? Environmental and Resource Economics 5, 95–113.

Turvey, R., 1963. On divergences between social cost and private cost. Economica 30, 309–323.

U.S. Army Corp of Engineers, 2002. NDC Publications and U.S. Waterway Data CD, Vol. 8. Institute for Water Resources Navigation Data Center.

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.