NAFTA Countries' Strategies for Addressing Marine Invasive Species through Shipping

Linda Fernandez
Dept. of Environmental Sciences
University of California, Riverside
Email: linda.fernandez@ucr.edu
Tel. (909)787-2955
Fax. (909)787-3993

Abstract

Maritime shipping has two vectors of spreading marine invasive species: ballast water inside the ship and biofouling on the hulls outside the ship. While some attention has focused on ballast water, virtually no effort has been made to address biofouling. This paper offers a quantitative analysis of economic incentives for shippers and regulating ports to address both vectors. The strategies to address the vectors are induced by incentive mechanisms involving liability, subsidies and taxes. Results show these offer ample incentives in order to truly foster abatement of both vectors. Data from North America's Pacific coast is included in the analysis.

Key Words: marine invasive species, shipping, incentive mechanisms

Ships transporting goods, people and services between different places represent a vector for spreading invasive species throughout the world's oceans (Hayes and Sliwa, 2003). Ships are mobile aquaria as species ranging from pathogens to fish hitchhike in ships' ballast water and attached to a ship's hulls as biofouling (Fofonoff et al., 2003). Ballast water helps keep boats stable to counteract the loading and unloading of cargo. Ballast water emissions release during the journey or upon arrival to a port is a "guaranteed" mechanism of inoculation where many invasive species are discharged into the receiving environment (Bax et al., 2003). Biofouling (invasive species adhering to a ship's hull) is potentially as harmful as ballast water in terms of invasive species (Fofonoff et. al., 2003). The main economic and social impacts of invasive species are negative impacts on human health and decreases in economic production activities based on marine environments and resources such as fisheries, aquaculture, tourism and marine infrastructure (Pimental et al., 2005). The economic magnitude of this problem is underscored by the estimate of $120 billion per year of costs due to land and aquatic invasive species (Pimental et al., 2005).

The General Accounting Office (2002) and the U.S. Commission on Ocean Policy note that the primary reason for the problems caused by marine invasive species is incomplete unilateral action for a transboundary pollution problem (U.S.COP, 2004). An example of unilateral action is California policy that requires mandatory reporting of ballast water exchange or other methods to treat ballast water emissions outside of the EEZ for vessels arriving to the state from outside of the Exclusive Economic Zone (EEZ), 200 miles away from the coast. Not all ships, however, discharge ballast water outside of the EEZ as suggested by policy. Approximately 50% of the vessels emitting ballast water upon arrival to California ports during the first six months of 2000 were from Japan, China and Korea. However, 50% of shipping traffic to California takes place *within* 200 miles of the coastal mainland, primarily from vessel traffic between Mexico and Canada, two of California's largest trading partners through the North American Free Trade Agreement (NAFTA) (GAO, 2002). These vessels are not subject to any guidelines for ballast water nor biofouling. Time and fuel considerations by shippers on the north-south route and lack of regulations governing invasive species introductions within the EEZ have not prevented the introduction of these species. For example, Levings et al. (2004) shows that ships traveling north from California and Mexico transport large numbers of invasive species into British Columbia, Canada. Therefore, current California policy to prevent the spread of marine invasive species is inadequate.

There are also known limitations to ballast water exchange to address emissions since new introductions have not been abated [U.S. COP, (2004), Taylor et al. (2002)]. Deepwater ballast exchange compliance may be low. Biofouling on ship hulls is not properly accounted for by policymakers as a harmful vector of invasive species emissions (Fofonoff et al., 2003; GAO, 2002).

Due to the nature of the threat posed by invasive species and the nature of global economic trade between NAFTA and Pacific Rim countries, new policies are needed to promote biosafety and address invasive species from a multinational scale. Recently in February 2004 an International Convention through the International Maritime Organization (IMO) formulated a numerical limit of emissions of 10 organisms per cubic meter of emissions in order to limit the transfer of organisms and opportunities of invasion with attention focused on ballast water emissions (Ambroggi, 2004). Biofouling emissions did not receive the same attention. Ultimately, the control effort at any scale will depend on the actions taken by shippers that in turn depend on economic incentives. The paper seeks to analyze the potential for invasive species management given the incentives on the part of shippers. The north-south route of maritime shipping along the Pacific coast of North America referred to in the introduction is a viable scale in which to examine policy alternatives for the study. The NAFTA trilateral Commission for Environmental Cooperation seeks to have a North American plan for addressing invasive species (CEC, 2003).

There is a paucity of economic analysis of invasive species, and virtually none on aquatic invasive species. Thus far, economic studies by Horan et al. (2002), Olson (2002), Perrings (2002), Lynch (2002), and Costello and McAusland (2003) of invasive species have focused on theoretical models of agricultural commodities that might harbor insects. These studies address intentional vectors of introduction for invasive species with a focus on establishing a hazard rate for eradication assuming arrival of an invasive species with the traded agricultural good. Transportation separate from the traded goods as a mode of unintentional species invasion has not been addressed in the economic literature. The models mentioned above do not allow for iterative invasions.

Preventative rather than reactive measures are necessary to control the spread of unintentional aquatic invasive species due to uncertainty of locating exact emissions per ship from both vectors (ballast water and biofouling) uniformly across time and space and eradicating these non-native species according to several natural scientists in the edited volume of Ruiz and Carlton (2003). Preventative policy measures exist but there has not been an economic analysis of their general cost effectiveness and the incentives for shippers and ports. Fernandez (2002) has studied the problem for ports deciding between preventative and reactive strategies. The paper will focus on the various incentives for publicly managed ports and private sector ship operators to control invasive species. The strategies to deal with invasive species will not only depend on the scales of vectors, but also the policy arena associated with these vectors. The scientific edited volume by Ruiz and Carlton (2003) concludes that a focus on vectors rather than species is imperative for policy because of the scientific uncertainties associated with the policy area.

There is room within the analytical framework to examine liability for damages caused by invasive species. Previous work by Segerson (1995) and Kolstad et al. (1990) address environmental damage liability unrelated to multiple vectors. The elements that Segerson (1995) describes for liability tied to a polluting firm that are relevant for invasive species are that unilateral care by the shipper matters for preventing damage and there is potential for a contractual arrangement between shipper and port that could formally internalize the externalities. The IMO has regulations related to the prevention, operation and maintenance for flagged states and ships (Llacer, 2004). The statutorily imposed liability for pollution through flagging and registering a ship for ocean transportation is the context for a more focused policy on invasive species. The ship is held liable regardless of the amount of care exercised. The form of joint and several liability where the court can apportion one party responsible for full damages regardless of relative contribution would make this parallel to strict liability for shippers.

Kolstad et al. (1990) investigate combining liability with an environmental standard. This paper addresses uncertainty and asymmetric information in the context of two emissions vectors (ballast water and biofouling) and more than one instrument is needed to address them. In this case, the optimal regulation consists of more than one part, dependent on information provided by the firm (Kolstad, 2000). Segerson (1995) indicates that the ex post nature of liability incentives are imperfect and combining with another instrument could be useful. Through measures of welfare and profit results it is possible to show that the policy instruments analyzed in this paper do not lead to trade distortions. The policies are already in place, but in need of finetuning to directly address the market failures focused specifically on invasive species. Existing budget channels are established for these policies.

A ship regardless of its location in the ocean is modeled for regulation. This is a context of an emission-differentiated regulation rather than an ambient differentiated regulation, though the overall levels of emissions under the IMO standard will still be controlled to achieve an environmental goal (Kolstad, 2000). The nonpoint source tax literature by Segerson (1988) extended by Cabe and Herriges (1992) and Horan (1998 and 2002) raises issues of ambient taxes that differ from this paper's point source emissions focus with liability.

Model

Interaction between regulating ports and shippers is modeled to accomplish preventative invasive species control through treatment. The choice of optimal regulatory policies with two vectors (ballast water and biofouling) of emissions is examined under conditions of (1) uncertainty regarding the potential magnitude of the externalities and (2) asymmetric information between the regulating port and the shipper regarding the shipper's potential liability for any damage costs. Therefore, it will be the case that a combination of two policies is used to address the market failures.

The model takes the IMO requirement on emissions as given and seeks to determine how best to regulate impacts from more than ballast water emissions in order to also address biofouling emissions. The analysis reflects the second best, fragmented nature of current environmental regulation. The shipper is assumed to know the standard to which he will be held in making his treatment decision. The environmental goal of the IMO standard on emissions from ships is a numerical goal of risk reduction in a safety-first manner, focused on ballast water.

The policy instruments used to regulate both biofouling and ballast water emissions externalities in the model are tied to existing policies. This analysis will suggest finetuning the policies in order to accomplish more complete and efficient abatement.

The goal of the regulating port is to minimize total social costs of shipping and any potential environmental impacts, subject to meeting the IMO standard. The shipper's objective is to maximize expected profits. Assume that shipping has constant returns technology, so any changes in shipping costs translate to changes in production costs per cubic meter of emissions.

The model addresses two cases. In the first model of regulation, there are not impacts from both vectors. In this case, the shipper simply chooses ballast water treatment to meet the IMO standard at least cost. In the model of regulation without ballast water emissions and biofouling emissions, the shipper's cost-minimizing selection matches the regulator's socially-optimal (in a second-best sense, given the level of the IMO standard) selection.

The second model considers a regulatory framework that may help regulating ports avoid some of the "unintended consequences" regarding uncontrolled invasive species. This second model allows for (1) the *possibility* of both ballast water emissions and biofouling emissions and (2) asymmetry regarding estimates of the shipper's potential *liability* for any invasive species impacts. Thus, the second model provides a more realistic description of most pollution regulation decisions. Liability can take the form of fines or penalties that makes it similar to enforcement schemes that impose penalties for accidents that occur (Segerson, 1995). In both models, functional forms are motivated by some empirics with properties for computational ease.

Regulation Without Multiple Vectors of Emissions

The shipper maximizes profits by selecting a combination of treatment of ballast water emissions $B_1$and biofouling emissions B_2 (definitions of symbols are provided in Table 1) to meet the IMO standard; in the case of lack of multiple vectors of invasive species emissions.

The model is developed on a "per cubic meter of emissions" basis to allow for aqueous emissions. Equation (1) below indicates that the shipper maximizes profit per cubic meter of emissions, π, by choosing to treat ballast water emissions B_1 in the tank and biofouling emissions B_2 from the hull dimensions of the ship. Equation (2) describes the IMO constraint, where $\bar{I}$ is the 10 organisms per cubic meter of emissions. Equation (2) describes the fixed-proportions relationship that exists between the emissions vectors and the standard $\bar{I}$. While the IMO attention has focused on B_1, it is useful to include B_2 . There are fixed dimensions of ballast water tank size and surface area for ships to follow the form of equation (2). For example, typically 30% of a ship's weight is the quantity of ballast water capacity for that ship (Langevin, 2003). Ballast capacity is greater than 100,000 cubic meters for ships along the west coast of North America (average is 350,000 cubic meters). The shipper's profit maximization problem is:

$$(1)\quad \max_{B_1,B_2} \pi = r - c_1B_1 - c_2B_2$$

$$(2)\quad \text{subject to} : a_1B_1 + a_2B_2 = \bar{I}$$

Parameter r in equation (1) is the shipper's profit margin per cubic meter of emissions (given typical ship capacity of hull and ballast tank dimensions). In this manner the shipper's earnings can be tied to the transportation activity he performs separately from the trade revenue. This is a useful distinction in order to investigate the transportation realm. The amount of shipping can be gauged by r and the following production relationship links emissions to shipping, r=F(V). The technology F(V) indicates the amount of emissions produced when the current shipping of the port is r in a manner that has been modeled in the environmental economics literature by Forster (1973) and Dockner and Long (1993). In this case, V is made up of both B_1 and B_2, according to $V=B_1+B_2$.

In 2003 the shipper's profit margin, r, was approximately $0.27 per cubic meter of emissions (reference). The IMO standard, $\bar{I}$, is set at 0.01, 10 organisms per cubic meter. Parameters a_1 and a_2 in the IMO standard represent how abatement via biofouling is credited relative to ballast water abatement, assuming these approaches are not perfect substitutes. Parameter a_1 is 0.36 percent per cubic meter of ballast water emissions, and a_2 is 0.19 percent per cubic meter of biofouling emissions. The cost parameters c_1 and c_2 in equation (1) are the per cubic meter treatment costs of ballast water emissions and biofouling emissions, respectively. Treatment implies the emissions are cleaned and released into the ocean. Shipper's treatment costs for biofouling emissions are 9-13 cents per cubic meter based on a range of six technology options for anti-fouling coatings that have different enzyme and phytochemical bases (Johnson and Miller, 2002). The cost of biofouling due to reduced fuel economy is 4 cents per cubic meter due to up to 10% drag that translates into a 1% loss of fuel from biofouling emisssions (Milne, 1990). This amount is then subtracted from the biofouling cost as a gain to fuel economy by the ship. Hence, c_2 , is set at the midpoint of the cost range, seven cents per cubic meter of biofouling emissions.[1] The coatings are variable costs in terms of the rate of application and maintenance, to release biofouling emissions off the hulls. In the event of fixed costs, they can be converted to annual figures using a discount rate of 5% for an equipment lifetime of 10 years. Then, it is possible to sum variable and fixed costs in the per cubic meter estimate of costs.

[1] Note that with the model parameter values described in the text, the estimate of biofouling emissions per cubic meter is an average of the range of biofouling treatment costs reduced by the fuel economy savings.

The cost of treating ballast water emissions, $c_{1,}$ is approximately \$2.39 per cubic meter of emissions, the midpoint of a range of a couple technology choices, that imply emissions are treated thereby lowering the concentration of invasive species compared to untreated emissions. Since ballast water exchange is not reliable it is important to include the costs of alternative technology that includes physical and chemical processes of deoxygenation and ultra violet treatment [(Taylor et al., 2002), (Tamburri et al., 2001)]. In this case, the variable and fixed costs are calculated on a per cubic meter basis for the cost range stated above that are applied to treat the volume of ballast water emissions, where the fixed costs are converted to annual costs to combine with variable costs by applying a 5% discount rate and an equipment lifetime of 20 years. Note, that certain options (filtration, heating) for ballast water emissions under 75,000 cubic meters are not possible for the volume of ballast water that ships on the Pacific coast of North America have.

The shipper's linear programming problem (1)-(2) implies a corner solution determined by the relative values of the parameters c_1, c_2, a_1 and a_2. When $a_1/c_1 < a_2/c_2$ (as is the case for ballast water emissions and biofouling emissions), the solution to the linear programming problem (1)-(2) is given by equations (3):

$$\text{(3)} \quad B_1^0 = 0, B_2^0 = \frac{\bar{I}}{a_2},$$

that is, the firm chooses to use $B_2^0 = 0.01$ per cubic meter of biofouling emissions (and zero percentage of ballast water) IMO standard $\bar{I}$. In the absence of emissions from both vectors, both the firm and the regulating port desire to use treat biofouling emissions to meet the IMO standard, at least cost.

Regulation With Both Biofouling and Ballast Water Emissions for Invasive Species

This case considers the shipper's ex-ante decision regarding emissions treatment and the regulating port's ex-ante decision regarding a regulatory policy designed to address the *potential* for both types of emissions (biofouling and ballast water). The IMO standard sets the goal for contending with damages from ballast water emissions only (IMO, 2004). Therefore, the following model includes damages from biofouling emissions explicitly in addition to damages from ballast water emissions accounted for in the IMO standard.

The Regulating Port's Problem

The regulating port defines expected social welfare E(W) as expected shipper profits less invasive species damages. Ex-post estimates of the invasive species damage cost are measured per cubic meter of biofouling emissions and these costs are quadratic in B_2 , that is, invasive species damages per cubic meter of biofouling emissions as $D \cdot (B_2)^2$. An index of invasive species damage severity, D, accounts for invasive species damaging native shellfisheries that have commercial, recreational, and existence value. Ex-post estimates of average invasive species damage costs range from \$0.06 to \$0.16 per cubic meter of biofouling emissions, including cleanup costs for the Pacific coast of North America [(Hanemann and Strand, 1993), (Department of Fisheries and Oceans Canada, 2002), (Estado de Baja, 2002), (Zentner et al., 2003)]. The upper limit of this range is considered a lower bound of actual damage costs due to limited data that does not cover the entire Pacific coast of the three NAFTA countries. Estimates from published studies for locations along the Pacific coast from the same time period that could be associated with a per cubic meter biofouling emissions in terms of impacts on production quantity and values of shellfisheries (market and nonmarket values are averaged for the damage measure. These estimates provide the factor income valuation approach where the per cubic meter marginal unit of biofouling emissions displaces a quantity of native shellfish that have the commercial and recreational value indicated in the estimates obtained for the damages.

In order to account for randomness, since damage is not deterministic, the following method is used. Taking the mid-point of the range of actual ex-post multiple externality damage cost estimates cited above, or \$0.11 per cubic meter of biofouling emissions, as the regulating port's ex-ante estimate of mean multiple externality damage costs per cubic meter of biofouling emissions, and recognizing that this mean damage cost corresponds to the actual amount of biofouling emissions, $B_2^0 = \frac{\bar{I}}{a_2} = 0.11$, enables solving for the mean value of the multiple externality damage severity index, denoted $\overline{D}$, as: $\$1.00 = \overline{D} \cdot (X_2^0)^2 = \overline{D} \cdot (0.11)^2 \Rightarrow \overline{D} = 82.64$. The 0.11 is per unit of aqueous biofouling emissions, while the \$1.00 is per unit dry weight of invasive species in aqueous biofouling emissions. The ex-post value of D is a random variable, ex-ante, from the perspective of both the port and the shipper. Suppose it is common knowledge, ex ante, that D follows an exponential probability density function with location parameter λ, (i.e., $p(D) = \lambda e^{-\lambda D}$) because this form has qualitative properties such as the shape that enables modeling unexpected events. For the exponential density function, $\overline{D}$ =1/λ; hence, λ = $1/\overline{D}$ = 0.0121, based on initial estimates of the damages to native shellfisheries, commercial and recreational values in Mexico, U.S. and Canada [Alaska Dept. of Fish and Game (2002), Department of Fisheries and Oceans Canada (2002), EDAW, Inc. (2003), Estado de Baja (2003), Hanemann (2003)]. The form of the probability density function indicates that the ex ante probability of small multiple externality damages is high, and the ex ante probability of large multiple vector damages is low. This form reflects situations in which ex-post multiple externality damage "surprises" are most likely to occur: namely, situations in which it is (mistakenly) "common knowledge," ex ante, that the probability of significant multiple vector damages is low.

With this specification of potential multiple vector damage costs, the port chooses ballast water emissions, B_1, and biofouling emissions, B_2, to maximize expected welfare subject to the IMO constraint. The regulating port's problem is:

$$(4)\quad \max_{B_1,B_2} E(W) = \int_0^{\infty}\left[r - c_1B_1 - c_2B_2 - DB_2^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$
$$\text{subject to}: a_1B_1 + a_2B_2 = \bar{I}\quad \text{(IMO constraint)}$$

Solving the constraint for B_2 and substituting into the objective function:

$$(5)\quad \max_{B_1} E(W) = \int_0^{\infty}\left[r - c_1B_1 - c_2\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right) - D\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right)^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD,$$

the first order condition for the problem is:

$$\frac{\partial E(W)}{\partial B_1} = \int_0^{\infty}\left[-c_1 + c_2\frac{a_1}{a_2} + 2D\frac{\bar{I}}{a_2}\left(\frac{a_1}{a_2}\right) - 2D\left(\frac{a_1}{a_2}\right)^2 B_1\right]\cdot\left(\lambda e^{-\lambda D}\right)dD \equiv 0,$$

or, defining $M_1 \equiv c_2(a_1/a_2) - c_1$, and distributing the integral across the terms of the integrand:

$$\frac{\partial E(W)}{\partial B_1} = M_1\cdot\int_0^{\infty}\left(\lambda e^{-\lambda D}\right)dD + \left[2\frac{\bar{I}}{a_2}\left(\frac{a_1}{a_2}\right) - 2\left(\frac{a_1}{a_2}\right)^2 B_1\right]\cdot\int_0^{\infty} D\cdot\left(\lambda e^{-\lambda D}\right)dD \equiv 0.$$

Evaluating the left-hand integral above via the method of u-substitution (with $u = -\lambda D$), and the right-hand integral via the method of integration by parts (with $u = D$ and $v = -e^{-\lambda D}$), leaves:

$$(6)\quad \frac{\partial E(W)}{\partial B_1} = M_1 + \left[2\frac{\bar{I}}{a_2}\left(\frac{a_1}{a_2}\right) - 2\left(\frac{a_1}{a_2}\right)^2 B_1\right]\left(\frac{1}{\lambda}\right) \equiv 0$$

Solving (6) for the port's optimal value of B_1:

$$(7)\quad B_1^* = \frac{M_1 + 2\dfrac{\bar{I}}{a_2}\left(\dfrac{a_1}{a_2}\right)\left(\dfrac{1}{\lambda}\right)}{2(a_1/a_2)^2\left(\dfrac{1}{\lambda}\right)}.$$

Equations (7) and (8) take into account damages, costs and relative contributions of ballast water emissions and biofouling emissions into the IMO limit, instead of just focusing on one vector of emissions.

The port's optimal value of B_2 is obtained via the IMO pollution regulation constraint:

$$(8)\quad B_2^* = (\bar{I}/a_2) - (a_1/a_2)B_1^*$$

The Unregulated Shipper's Problem

The form of shipper's liability is joint and several liability where the share of costs under the liability rule lies between zero and one, and the shipper's expectation is that the share is α. Without regulation, the shipper chooses B_1 and B_2 to maximize expected profit (including any multiple vector damages for which the shipper is liable), $E(\pi)$, subject to the IMO regulation constraint and its anticipated share of any multiple externality damages:

$$(9)\quad \max_{B_1,B_2} E(\pi(= \int_0^{\infty}\left[r - c_1B_1 - c_2B_2 - \alpha D B_2^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$
$$\text{subject to}: a_1B_1 + a_2B_2 = \bar{I} \quad \text{(IMO pollution constraint)}$$

Solving the unregulated shipper's problem using methods analogous to those used in the port's problem above, the unregulated shipper's profit-maximizing values of B_1 and B_2, denoted $\hat{B}_1$ and $\hat{B}_2$, are given by:

$$(10)\quad \hat{B}_1 = \frac{M_1 + 2\alpha(\bar{I}/a_2)(a_1/a_2)(1/\lambda)}{2\alpha(a_1/a_2)(1/\lambda)}, \quad \hat{B}_2 = (\bar{I}/a_2) - (a_1/a_2)\hat{B}_1$$

If the shipper's anticipated liability share $\alpha = 1$, that is, if the shipper expects to bear full liability for any and all multiple vector damage costs, then the unregulated shipper's choices of B_1 and B_2

correspond to the shipper's optimal values B_1^* and B_2^*. However, as the shipper's anticipated liability share α decreases, $\hat{B}_1$ decreases and $\hat{B}_2$ increases, deviating from the socially-optimal values for treatment of B_1^* and B_2^*. Thus, strict liability encourages precaution through treatment when there is a risk of damages. Joint and several liability may result in less than optimal treatment of both biofouling and ballast water emissions. Preventative action with liability could take place within the existing framework of ship registration. The registration involves certifying security measures that include addressing marine pollution. The International Ship and Port Facility Security Code that ships must abide by July 1, 2004 (IMO, 2002), could emphasize that ships maintains pollution control in order to be able to engage in shipping activity.

The Regulated Shipper's Problem

The regulator uses a subsidy[2], s, per unit of B_1 to ensure that the firm's chosen levels of B_1 and B_2 are consistent with the planner's optimal levels B_1^* and B_2^*. The subsidy is viable through an existing program such as the Experimental Ballast Water Treatment Systems STEP Program run by the U.S. Coast Guard for allocating funds to offset costs of alternative treatment technology (U.S. Coast Guard, 2004). As shown below, the socially-optimal subsidy depends on the shipper's anticipated liability share for invasive species damages α. Since the instrument is on a per cubic meter unit basis, it enables flexibility for the shipper to choose amongst technology alternatives depending on vessel characteristics (surface area and ballast water capacity). In this manner, the instruments allow for heterogeneity of ships and can be considered more efficient than a uniform instrument. There is asymmetric information between the shipper

[2]Ballast water reporting and offloading fees for ships according to the California State Lands Commission are lower than actual costs, thereby representing a subsidy.

and the regulating port regarding α. The shipper's *true* anticipated liability share α_t is known only to the shipper due to the abatement choices made. The shipper may choose to *report* a liability share α_r different from the *true* share α_t in an attempt to manipulate the regulating port and increase expected firm profits. This is plausible feature of the model since the existing W. Coast Ballast Water Reporting Program simply collects information that shippers report to ports, no verification is made. In addition to the per unit subsidy s, the regulating port pays the firm a lump-sum subsidy[3] S (derived below) to ensure that the shipper reports its true anticipated liability share. (It is shown below that both s and S are functions of α, that is, s(α) and S(α).) The regulated shipper's problem is to maximize expected profit, including any multiple vector damage liability, ballast water subsidy s, and lump-sum subsidy S, by choosing B_1 and B_2 subject to the IMO regulation constraint:

$$(11)\quad \max_{B_1,B_2} E(\pi(= \int_0^\infty \left[r-(c_1-s(\alpha_r))B_1 - c_2B_2 - \alpha_t D B_2^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

$$\text{subject to}: a_1B_1 + a_2B_2 = \bar{I} \quad \text{(IMO constraint)}$$

Solving the IMO constraint for B_2 and substituting into the objective function:

(12)

$$\max_{B_1} E(\pi(= \int_0^\infty \left[r-(c_1-s(\alpha_r))B_1 - c_2\left(\frac{\bar{I}}{a_2}-\frac{a_1}{a_2}B_1\right) - \alpha_t D\left(\frac{\bar{I}}{a_2}-\frac{a_1}{a_2}B_1\right)^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

The FOC for the problem is:

[3] Since the model is parameterized on a cubic meter basis, this subsidy is drawn from an existing ballast water reporting fee uniformly charged per boat that is set purposely low simply to cover some administration costs (California State Lands Commission, 2003). However, it is reasonable to assume that this fee can be adjusted based on the potential severity of invasive species costs. For example, there has been discussion that the current fee of \$0.012 per cubic meter of untreated ballast water is not sufficient to cover cleanup costs or reporting costs for all boats, and it could be raised to a range of \$0.048-\$0.21. The lump-sum subsidy S discussed in the model can be envisioned as a *reduction* in the ballast water fee.

(13) $$\frac{\partial E(W)}{\partial B_1} = \int_0^{\infty}\left[M_1 + s(\alpha_r) + 2\alpha_t D\frac{\bar{I}}{a_2}\left(\frac{a_1}{a_2}\right) - 2\alpha_t D\left(\frac{a_1}{a_2}\right)^2 B_1\right]\cdot\left(\lambda e^{-\lambda D}\right)dD \equiv 0$$

Solving the regulated shipper's problem using methods analogous to those used in the social planner's problem, the regulated shipper's profit-maximizing values of B_1 and B_2, denoted $\overline{B}_1$ and $\overline{B}_2$, are given by:

(14) $$\overline{B}_1 = \frac{M_1 + s(\alpha_t) + 2\alpha(\bar{I}/a_2)(a_1/a_2)(1/\lambda)}{2\alpha(a_1/a_2)(1/\lambda)},\ \overline{B}_2 = (\bar{I}/a_2) - (a_1/a_2)\overline{B}_1$$

The difference between these values and those in equation (10) is that the subsidy in the numerator of B_1 will mean more abatement is accomplished. Equation (14) indicates that the marginal savings to the shipper from the amount of ballast water emissions and biofouling emissions is equality the contribution to the emissions target, taking into account the subsidy.

The Port's Choice of Per-Unit Ballast Water Subsidy s

The port determines the per-unit ballast water subsidy rule $s(\alpha_r)$ necessary to ensure that $\overline{B}_1 = B_1^*$ under the assumption that the lump-sum subsidy $S(\alpha_r)$ (derived below) will ensure that the shipper will report its true liability share, that is, under the assumption that $\alpha_r = \alpha_t$ (this assumption is verified in Appendix 1).

$$\overline{B}_1 = B_1^*$$

$$\frac{M_1 + s(\alpha_t) + 2\alpha(\bar{I}/a_2)(a_1/a_2)(1/\lambda)}{2\alpha(a_1/a_2)(1/\lambda)} = \frac{M_1 + 2\alpha(\bar{I}/a_2)(a_1/a_2)(1/\lambda)}{2\alpha(a_1/a_2)(1/\lambda)}$$

(15) $$s(\alpha_r) = -(1-\alpha_r)\cdot M_1$$

Since $M_1 = c_2(a_1/a_2) - c_1$, the subsidy in the numerator would be adjusted according to α.

The Regulated Shipper's Choice of Reported Liability α_r

The regulated shipper knows that the regulator's per unit subsidy rule $s(\alpha_r)$ and lump-sum subsidy $S(\alpha_r)$ depend on the shipper's report α_r. The shipper chooses α_r to maximize $E(\pi(\overline{B}_1, \overline{B}_2))$. Recalling expression (11) above, the shipper's problem is now:

$$(16) \quad \max_{\alpha_r} E(\pi(\overline{B}_1, \overline{B}_2)) = \int_0^{\infty} \left[r - (c_1 - s(\alpha_r))\overline{B}_1 - c_2 \overline{B}_2 - \alpha_t D \overline{B}_2^2 + S(\alpha_r) \right] \cdot \left(\lambda e^{-\lambda D} \right) dD$$

Using the IMO constraint to substitute for $\overline{B}_2$, the shipper's problem becomes:

$$\max_{\alpha_r} E(\pi(\overline{B}_1)) = \int_0^{\infty} \left[r - (c_1 - s(\alpha_r))\overline{B}_1 - c_2 \left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2} \overline{B}_1 \right) - \alpha_t D \left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2} \overline{B}_1 \right)^2 + S(\alpha_r) \right] \cdot \left(\lambda e^{-\lambda D} \right) dD$$

The first order condition for this problem is:

$$(17) \quad \frac{\partial E(\pi(\vec{B}_1))}{\partial \alpha_r} = \int_0^{\infty} \left[M_1 \frac{\partial \overline{B}_1}{\partial s} \frac{\partial s}{\partial \alpha_r} + \frac{\partial s}{\partial \alpha_r} \overline{B}_1 + s \frac{\partial \overline{B}_1}{\partial s} \frac{\partial s}{\partial \alpha_r} + \alpha_t M_2 \frac{\partial \overline{B}_1}{\partial s} \frac{\partial s}{\partial \alpha_r} \right.$$

$$\left. - 2\alpha_t M_3 \overline{B}_1 \frac{\partial \overline{B}_1}{\partial s} \frac{\partial s}{\partial \alpha_r} + \frac{\partial S}{\partial \alpha_r} \right] \cdot \left(\lambda e^{-\lambda D} \right) dD \equiv 0 ,$$

where $M_2 \equiv 2D(\bar{I}/a_2)(a_1/a_2)$, and $M_3 \equiv D(a_1/a_2)^2$. Expression (17) implicitly defines the regulated shipper's profit-maximizing choice of α_r. However, solving explicitly for α_r will not occur because, under the incentive mechanism, the lump-sum subsidy S offered by the regulating port to the shipper will ensure that α_r equals α_t, as shown in Appendix 1.

The Port's Choice of Lump-Sum Subsidy S

Under the assumption that the lump-sum subsidy S ensures that $\alpha_r = \alpha_t$, the regulated shipper's expected profit $E(\pi(\overline{B}_1))$ varies with its ***true*** liability share α_t as:

(18)

$$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \int_0^\infty \Bigg\{ M_1\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + \frac{\partial s}{\partial \alpha_t}\overline{B}_1 + s\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + M_2\overline{B}_1 + \alpha_t M_2\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right]$$

$$- M_3\overline{B}_1^2 - 2\alpha_t M_3\overline{B}_1\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] - D(\bar{I}/a_2)^2 + \frac{\partial S}{\partial \alpha_t}\Bigg\} \cdot \left(\lambda e^{-\lambda D}\right) dD$$

As the lump-sum subsidy S (derived below) ensures that $\alpha_r = \alpha_t$ (as verified in Appendix 1), (17) helps simplify (18) via the envelope theorem yielding:

(19) $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \int_0^\infty \Bigg\{ - D(\bar{I}/a_2)^2 + M_1\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + s\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + M_2\overline{B}_1 + \alpha_t M_2\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right]$$

$$- M_3\overline{B}_1^2 - 2\alpha_t M_3\overline{B}_1\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right]\Bigg\} \cdot \left(\lambda e^{-\lambda D}\right) dD$$

Recognizing that $\frac{\partial \overline{B}_1}{\partial \alpha_t} = \frac{-M_1}{2\alpha_t (a_1/a_2)^2 (1/\lambda 1}$, expression (19) becomes:

(20) $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \int_0^\infty \left\{ \frac{DM_1^2 - 2M_1^2(1/\lambda)}{4(a_1/a_2)^2 (1/\lambda)^2} \right\} \cdot \left(\lambda e^{-\lambda D}\right) dD,$$

or, $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \left(\frac{M_1^2}{4(a_1/a_2)^2}\right)\int_0^\infty \left\{\frac{D}{(1/\lambda)^2}\right\} \cdot \left(\lambda e^{-\lambda D}\right) dD - \left(\frac{M_1^2}{2(a_1/a_2)^2}\right)\int_0^\infty \{\lambda\} \cdot \left(\lambda e^{-\lambda D}\right) dD \cdot$$

Evaluating the left-hand integral in the expression above via the method of integration by parts (with u = D and $v = -e^{-\lambda D}$), and the right-hand integral via the method of u-substitution (with u = $-\lambda D$), leaves:

(21) $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \frac{-M_1^2}{4(a_1/a_2)^2 (1/\lambda)}.$$

Defining the portion of $E(\pi(\overline{B}_1))$ that varies with α as:

$$(22)\quad \int_0^{\infty}\left[-(c_1 - s(\alpha_r))\overline{B}_1 - c_2\left(-\frac{a_1}{a_2}\overline{B}_1\right) - \alpha_t D\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}\overline{B}_1\right)^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD\,.$$

Expression (22) is equal to the integral of expression (21) multiplied by the density function of α, p(α), where p(α) is uniformly distributed over support (0,1), and where the integral is taken over α from α = 0 to $\alpha = \alpha_t$, that is:

$$(23)\quad \int_0^{\infty}\left[-(c_1 - s(\alpha_r))\overline{B}_1 - c_2\left(-\frac{a_1}{a_2}\overline{B}_1\right) - \alpha_t D\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}\overline{B}_1\right)^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

$$= \int_0^{\alpha_t}\frac{-M_1^2}{4(a_1/a_2)^2(1/\lambda)}\cdot p(\alpha)\,d\alpha\,\cdot$$

Evaluating the integral on the left-hand side of expression (23), and recalling that $p(\alpha) = \dfrac{1}{1-0}$ for a uniform distribution with support (0,1), expression (23) becomes:

$$-(c_1 - s(\alpha_r))\overline{B}_1 + c_2\left(\frac{a_1}{a_2}\right)\overline{B}_1 - \alpha_t\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}\overline{B}_1\right)^2 + S(\alpha_r) = \int_0^{\alpha_t}\frac{-M_1^2}{4(a_1/a_2)^2(1/\lambda 1}\cdot\left[\frac{1}{1-0}\right]d\alpha\;\cdot$$

Evaluating the integral on the right-hand side of the expression above, yields:

$$(24)\quad -(c_1 - s(\alpha_r))\overline{B}_1 + c_2\left(\frac{a_1}{a_2}\right)\overline{B}_1 - \alpha_t\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}\bar{I}_1\right)^2 + S(\alpha_r) = \frac{-B_1^2\alpha_t}{4(r_1/r_2)^2(1/\lambda)},$$

from which the port's rule for determining the lump-sum subsidy S as a function of the shipper's reported value of α is recovered:

$$(25)\quad S(\alpha_r) = (c_1 - s(\alpha_r))\overline{B}_1 - c_2\left(\frac{a_1}{a_2}\right)\overline{B}_1 + \alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}\overline{B}_1\right)^2 - \frac{M_1^2\alpha_r}{4(a_1/a_2)^2(1/\lambda)}$$

This subsidy offered for the shipper to abate can be seen as an alternative to searching for an optimal auditing policy that would need some probability that an audit will be carried out.

The Regulated Shipper's Expected Profit $E(\pi(\overline{B}_1))$ Under the Incentive Mechanism

The regulated shipper's expected profit under the incentive mechanism $E(\pi(\overline{B}_1))$ is found by adding the portion of $E(\pi(\overline{B}_1))$ that varies with α, equivalent to the right-hand side of expression (24), to the portion of $E(\pi(\overline{B}_1))$ that does <u>not</u> vary with α, namely $r-(c_2\overline{I}/a_2)$:

(26) $$E(\pi(\overline{B}_1)) = r-(c_2\overline{B}/a_2) - \frac{M_1^2\alpha_t}{4(a_1/a_2)^2(1/\lambda 1}$$

The ideal regulation is one with incentive (expected profit) for the shipper to reveal the truth.

A Per-unit Tax on X_2 and a Lump-Sum Fee

The Regulating Port's Problem

The regulating port's problem under tax regulation is identical to that under subsidy regulation and produces identical results B_1^*, B_2^*.

The Unregulated Shipper's Problem

The unregulated shipper's problem under tax regulation is identical to that under subsidy regulation and produces identical results: B_1^*, B_2^*. As the unregulated shipper's anticipated liability share α decreases from its maximum value of 1, $\hat{B}_1$ decreases and $\hat{B}_2$ increases, deviating from their socially-optimal values B_1^*, B_2^* .

The Regulated Shipper's Problem Under Tax Regulation

The port uses a per unit tax, t, assessed per unit of B_2, to ensure that the shipper's chosen levels of B_1 and B_2 are consistent with socially-optimal levels B_1^*, B_2^*. As shown below, the socially-optimal tax depends on the shipper's anticipated liability share for multiple vector damages α. There is asymmetric information between the shipper and the port regarding α. The firm's *true* liability share α_t is known only to the shipper. In addition to the per unit tax t, the port imposes a lump-sum fee F (derived below) on the shipper to ensure that the shipper reports the true liability share. It is shown below that both the per unit tax t and the optimal lump-sum fee are functions of α, that is, $t(\alpha)$ and $F(\alpha)$. The shipper may choose to *report* a liability share α_r different from the *true* share α_t in an attempt to manipulate the port's choice of t and F and increase shipper profit. The shipper's problem under tax regulation is to maximize expected profit $E(\pi)$, including any invasive species damage liability, per-unit ballast water tax t, and lump-sum fee F, by choosing B_1 and B_2 subject to the IMO constraint:

$$(27)\quad \max_{B_1,B_2} E(\pi(= \int_0^\infty \left[r - c_1B_1 - (c_2 + t(\alpha_r))B_2 - \alpha_t DB_2^2 - F(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

$$\text{subject to}: a_1B_1 + a_2B_2 = \bar{I} \quad \text{(IMO constraint)}$$

Solving the constraint for B_1 and substituting into the objective function:

$$(28)\quad \max_{B_2} E(\pi(= \int_0^\infty \left[r - c_1\left(\frac{\bar{I}}{a_1} - \frac{a_2}{a_1}B_2\right) - (c_2 + t(\alpha_t))B_2 - \alpha_t DB_2{}^2 - F(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

The FOC for the problem is:

$$(29)\quad \frac{\partial E(\pi(}{\partial B_2} = \int_0^\infty \left[M_4 - t(\alpha_r) - 2\alpha_t DB_2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD \equiv 0, \qquad \text{where} \quad M_4 \equiv c_1a_2/a_1 - c_2.$$

Evaluating the integral in (29) using methods analogous to those used in section 2.2.a of the text, the resulting expression for the shipper's profit-maximizing values of B_1 and B_2 is solved under tax regulation, denoted $\ddot{B}_1$ and $\ddot{B}_2$:

$$(30)\quad \ddot{B}_2 = \frac{M_4 - t(\alpha_r)}{2\alpha_t(1/\lambda)}, \qquad \dddot{B}_1 = (\bar{I}/a_1) - (a_2/a_1)\dddot{B}_2$$

From equation (30), the level of both types of emissions is based on the marginal benefit to the firm equal to the marginal expected tax, taking into account liability and the contributions of these emissions to the IMO standard.

The Port's Choice of Per-Unit tax t

The port determines the per unit tax $t(\alpha_r)$ necessary to ensure that $\dddot{B}_2 = B_2^*$ under the assumption that the lump-sum fee $F(\alpha_r)$ (derived below) will ensure that $\alpha_r = \alpha_t$:

$$\dddot{B}_2 = B_2^*$$

$$\frac{M_4 - t(\alpha_r)}{2\alpha_t(1/\lambda)} = \frac{M_4}{2(1/\lambda)}$$

(31) $t(\alpha_r) = (1 - \alpha_r) \cdot M_4$

The Shipper's Choice of Reported Liability α_r

The regulated shipper knows that the port's per unit tax rule $t(\alpha_r)$ and lump-sum fee $F(\alpha_r)$ depend on the shipper's report α_r. The regulated shipper chooses α_r to maximize $E(\pi(\dddot{B}_1, \dddot{B}_2))$. Recalling expression (28) above:

(32)
$$\max_{\alpha_r} E(\pi(\dddot{B}_1(\dddot{B}_2), \dddot{B}_2)) = \int_0^\infty \left[r - c_1\left(\frac{\bar{I}}{a_1} - \frac{a_2}{a_1} \cdot \dddot{B}_2(s(\alpha_r), \alpha_t)\right) \right.$$
$$\left. - (c_2 + t(\alpha_r)) \cdot \dddot{B}_2(s(\alpha_r), \alpha_t) \; - \alpha_t D\left(\dddot{B}_2(s(\alpha_r), \alpha_t)\right)^2 - F(\alpha_r) \right] \cdot \left(\lambda e^{-\lambda D}\right) dD$$

The first order condition for this problem is:

(33)

$$\frac{\partial E(\pi(\dddot{B}_2))}{\partial \alpha_r} = \int_0^\infty \left[M_4 \frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_r} - \frac{\partial t}{\partial \alpha_r} \dddot{B}_2 - t \cdot \frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_r} - 2\alpha_t D \dddot{B}_2 \frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_r} - \frac{\partial F}{\partial \alpha_r} \right] \cdot \left(\lambda e^{-\lambda D}\right) dD \equiv 0$$

Expression (33) implicitly defines the shipper's profit-maximizing choice of α_r under tax regulation. However, there is no point in solving explicitly for α_r because, under the incentive mechanism, the lump-sum fee F offered by the port to the shipper will ensure that the shipper's reported α_r equals the true α_t , that is, $\alpha_r = \alpha_t$, as verified below.

The Port's Choice of Lump-Sum Fee F

Under the assumption that the lump-sum fee F ensures that $\alpha_r = \alpha_t$, the regulated shipper's expected profit $E(\pi(\dddot{B}_2(\alpha_t)))$ varies with the ***true*** liability share α_t as:

(34)
$$\frac{\partial E(\pi)}{\partial \alpha_t} = \int_0^\infty \left\{ M_4 \left[\frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_t} + \frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - \frac{\partial t}{\partial \alpha_t} \dddot{B}_2 - t \cdot \left[\frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_t} + \frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - 2\alpha_t D \dddot{B}_2 \left[\frac{\partial \dddot{B}_2}{\partial t} \frac{\partial t}{\partial \alpha_t} + \frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - D\dddot{B}_2^{\,2} - \frac{\partial F}{\partial \alpha_t} \right\} \cdot \left(\lambda e^{-\lambda D} \right) dD$$

As the lump-sum fee F (derived below) ensures that $\alpha_r = \alpha_t$ (as verified below), we may use (33) to simplify (34) via the envelope theorem to find:

(35)
$$\frac{\partial E(\pi)}{\partial \alpha_t} = \int_0^\infty \left\{ M_4 \left[\frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - t \cdot \left[\frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - 2\alpha_t D \dddot{B}_2 \left[\frac{\partial \dddot{B}_2}{\partial \alpha_t} \right] - D\dddot{B}_2^{\,2} \right\} \cdot \left(\lambda e^{-\lambda D} \right) dD$$

Recognizing that $\frac{\partial \dddot{B}_2}{\partial \alpha_t} = \frac{-M_4}{2\alpha_t(1/\lambda)}$, and evaluating the integral in expression (35) using methods analogous to those in section 2.2.a., yields:

(36)
$$\frac{\partial E(\pi)}{\partial \alpha_t} = \frac{-M_4^2}{4(1/\lambda)}.$$

Define *the portion of E(π) that varies with α* as:

(37)
$$\int_0^\infty \left[c_1(a_2/a_1)\dddot{B}_2 - (c_2 + t(\alpha_t))\dddot{B}_2 - \alpha_t D \dddot{B}_2^{\,2} - F(\alpha_r) \right] \cdot \left(\lambda e^{-\lambda D} \right) dD.$$

Expression (37) is equal to the integral of expression (36) multiplied by the density function of α, $p(\alpha)$, where $p(\alpha)$ is uniformly distributed over support (0,1), and where the integral is taken over α from $\alpha = 0$ to $\alpha = \alpha_t$, that is:

(38) $$\int_0^{\infty}\left[c_1(a_2/a_1)\dddot{B}_2 - (c_2 + t(\alpha_t))\dddot{B}_2 - \alpha_t D\ddot{B}_2^{\,2} - F(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

$$= \int_0^{\alpha_t}\frac{-M_4^2}{4(1/\lambda)}\cdot p(\alpha)\,d\alpha \quad = \quad \int_0^{\alpha_t}\frac{-M_4^2}{4(1/\lambda)}\cdot\left[\frac{1}{1-0}\right]d\alpha \quad = \quad \left.\frac{-M_4^2\alpha}{4(1/\lambda)}\right|_0^{\alpha_t} \quad = \quad \frac{-M_4^2\alpha_t}{4(1/\lambda)}.$$

After evaluating the integral on the left-hand side of (38), the regulating port's rule for determining the fixed fee F as a function of the shipper's reported value of α is found:

(39) $$F(\alpha_r) = c_1(a_2/a_1)\dddot{B}_2 - (c_2 + t(\alpha_r))\dddot{B}_2 - \alpha_r(1/\lambda)\ddot{B}_2^{\,2} + \frac{M_4^2\alpha_r}{4(1/\lambda)}$$

The Regulated Shipper's Expected Profit E(π) Under the Incentive Mechanism

The regulated shipper's expected profit under the incentive mechanism $E(\pi(\ddot{B}_2))$ is found by adding *the portion of E(π) that varies with α,* equivalent to the right hand side of expression (38), to *the portion of E(π) that does <u>not</u> vary with α*, namely $r - (c_1\bar{I}/a_1)$:

(40) $$E(\pi(\ddot{B}_2)) = r - (c_1\bar{I}/a_1) - \frac{M_4^2\alpha_t}{4(1/\lambda)}$$

Numerical Results for the Multiple Ship Externality Model

The model parameter values mentioned in the previous sections are derived from several data sources. The cost parameters for ballast water emissions and biofouling emissions are based on the dimensions of ships of different sizes in terms of surface area of hulls for biofouling treatment costs and volume of ballast water for the ships entering NAFTA Pacific ports (Seattle, San Francisco, Los Angeles, Long Beach, Vancouver, Ensenada) [(U.S. Maritime Administration, (2001), Lloyd's Register World Fleet Statistical Tables, (2002)]. Alternative options to ballast water exchange include various mechanical, physical, chemical or biological procedures [(Ruiz et al., 2001), (Rigby and Taylor, 2001, (Tamburri et al., 2002)]. Costs associated with biofouling technology are unit costs of labor and hull cleaning material (Johnson and Miller, 2002).

The results in Table 2 are based on the multiple emissions vectors parameter values discussed in preceding sections of the paper for Pacific North American ports: $r = 0.65$, $c_1 = \$2.39$, $c_2 = \$0.07$, $a_1 = 0.36$, $a_2 = 0.19$, $\bar{I} = 0.01$, $B_2^0 = 0.11$ and $\lambda = 0.0121$.

Table 2 results are presented in four panels. Panel a gives the regulating port's choice of per-unit ballast water subsidy s and lump-sum subsidy S based on the shipper's reported multiple vector damage liability share α_r. Notice that the subsidies vary inversely with respect to one another as the shipper reports larger values of α_r. If the shipper reports a small value of α_r, that is, if the shipper reports that its liability share for multiple vector damages will likely be small, then a large per-unit ballast water subsidy, s, is chosen by the regulating port, because an unregulated shipper would otherwise largely discount multiple vector damages and select an inefficiently low level of ballast water treatment and an inefficiently high level of biofouling treatment. As the shipper's reported value of α_r increases, the shipper's increasing liability for multiple vector damages serves as an increasingly sufficient incentive for the firm to select the socially-optimal combination of ballast water emissions and biofouling emission to be treated. As a result, the per-unit ballast water subsidy necessary to ensure that the firm selects the socially-optimal combination of treatment decreases.

If the regulator relied on the ballast water subsidy alone as the sole policy instrument, the firm would have an incentive to report small values of α regardless of the true liability share in order to manipulate the regulating port into providing large ballast water subsidies. The regulating port uses the lump-sum subsidy S to combat the shipper's incentive to report false values of α. If the shipper's reported value α_r is small, the shipper receives a large lump-sum subsidy. The size of the lump sum subsidy decreases as the shipper reports larger values of α. As shown in the model description, the regulating port's rules for selecting values of s and S that vary inversely with one another ensure that the shipper cannot increase its profits by reporting a false value of α.

Panels b and c of Table 2 illustrate how the shipper's ballast water treatment B_1 and biofouling emissions B_2 vary with the shipper's true invasive species damage liability share α_t and the shipper's reported liability share α_r. As the shipper's true vector liability share α_t increases, the shipper treats more ballast water B_1, which helps reduce pollution, and treats biofouling B_2 , which does have the potential to exacerbate pollution. As the shipper's reported liability share α_r increases, the shipper receives smaller ballast water subsidies, and as a result the shipper treats less B_1 and more B_2.

The results presented in panel d of Table 2 confirm that the shipper cannot increase its expected profit $E(\pi)$ by reporting a liability share α_r that differs from the shipper's true liability share α_t . As a result, it is assumed that the shipper will report its true liability share. The results in panel d indicate that as the shipper's true liability share increases, the shipper's expected profit decreases under the incentive mechanism.

The diagonal elements of panels b and c give the shipper's chosen values of B_1 and B_2 under the incentive mechanism, that is, when $\alpha_r = \alpha_t$. As the shipper's true liability share increases when under the incentive mechanism, the shipper's socially-optimal selections of B_1 and B_2 do not change—the true liability share influences the distribution of rents between the firm and the rest of society, but it does not influence the determination of socially-optimal activity levels.

As indicated by the results in panel a, in order to implement the incentive mechanism, the regulating port would have needed to pay the shipper a per-unit subsidy s of from \$0.01 to \$0.54 per cubic meter of ballast water emissions (equivalent to 5/100ths of a cent to 3 cents per cubic meter of ballast water) and a lump-sum subsidy S of from \$0.02 to \$0.04 per cubic meter.

Conclusions

There is potential for incentive mechanisms to help ports avoid unintended consequences of invasive species in situations involving uncertain damages and asymmetric information between ports and shippers.

The incentive mechanism can involve a combination of liability with subsidies or liability with taxes. The port's selected values of the two subsidies (a lump sum and per cubic meter) vary inversely with one another to ensure that the shipper reports a true estimate of its invasive species damage liability. As the shipper's liability increases, the shipper's expected profit decreases under the incentive mechanism. However, when shipper's liability is high, a shipper regulated under the incentive mechanism earns higher profits than would an unregulated firm. Changes in liability do not affect the shipper's socially-optimal selections of treatment—liability influences the distribution of rents between the shipper and the rest of society, but it does not influence the determination of socially-optimal activity levels. The benefits of regulation to the shipper are higher when liability and invasive species damages are high.

Alternatively, benefits of regulation in terms of social welfare are higher when liability and invasive species damages are low.

Although the subsidy-based mechanism achieves the (second-best) social optimum, there are alternative mechanisms such as taxes that achieve the same efficiency result with different equity outcomes. Under the tax-based mechanism, a per-unit tax of 0.5 to 28 cents per cubic meter in combination with a lump-sum fee of 0.05 to 0.10 cents (panel a, Table 3), depending on the shipper's multiple vector damage liability, result in the shipper's selection of the socially-optimal combination of treatment (compare panels b and c of Table 2 and Table 3). Of course, under the tax-based mechanism, the shipper's profits are lower (compare panel d in Table 2 with panel d in Table 3), but expected social welfare remains the same (compare panel e in Table 2 with panel e in Table 3). The tax-based model shows that the same efficiency result can be achieved in alternative ways depending on equity goals and other constraints.

The implementation of the liability, subsidy and tax incentive mechanisms can occur through existing but refined policies. Currently, the port fee for reporting ballast water treatment and offloading does not depend on the shipper's reported liability. However, this fee could be adjusted to correspond to the lump-sum fee in the tax-based incentive mechanism to induce the shipper to reveal its true liability. The subsidy for technology is not set according to a measure of actual impact of invasive species, and this amount could be modified to accomplish the abatement that is indicated in this analysis in order to properly address marine invasive species through both shipping vectors. The recent U.S. Commission on Ocean Policy suggests collecting adequate levels of resource rent for ocean space in terms of the port access fees that can be used to protect the public ocean (U. S. COP, 2004). The tax mechanisms suggested here can serve towards this goal.

The purpose of the model presented here is to provide an illustration of how incentive mechanisms might be applied to "real-world" invasive species regulation. It is possible to transfer this model to other settings beyond the Pacific Coast of North America that provided some empirical reference for this study. Of course, the transfer would be made with appropriate adjustment of the number and definition of choice variables, specification of functional forms, sources of uncertainty and asymmetric information, etc.

The model considered here operates in a second best world with a new IMO numerical standard. Further investigation could examine relaxing the standard and optimizing. To do so, it would be necessary to consider additional information on comprehensive values of damages.

References

Alaska Dept. of Fish and Game, Division of Commercial Fisheries. (2002). Overview of 2002, available at www.Cf.adfg.state.ak.us/geninfo/budget/02overview.pdf.

Ambroggi, S. (2004). "UN Agrees on Laws Against "Alien " Marine Invaders." February 16, 2004 Reuters News Service.

Bax, N., A. Williamson, M. Aguero, E. Gonzalez, and W. Geeves. (2003). "Marine Invasive Alien Species: A Threat to Global Biodiversity." *Marine Policy* 27, 313-323.

Cabe, R. and J. Herriges. (1992). "The Regulation of Non-Point-Source Pollution under Imperfect and Asymmetric Information," *Journal of Environmental Economics and Management*, 22:134-146.

California State Lands Commission. (2003). Marine Invasive Species Control Fund Fee. Article 4.5, Section 2270.

Costello, C. and C. McCausland. (2003). "Protectionism, Trade and Measures of Damage from Exotic Species Introductions." *American Journal of Agricultural Economics* 85(4).

Commission for Environmental Cooperation. (2003) "Closing the Pathways of Aquatic Invasive Species across North America," CEC, Montreal.

Department of Fisheries and Oceans Canada. (2002). Summary of Canadian Commercial Catches, Fisheries Statistics, Fisheries and Oceans Canada, Ottawa, Canada.

Dockner, E. and N. van Long (1993). "International Pollution Control: Cooperative Versus Noncooperative Strategies," *Journal of Environmental Economics and Management*, 25.

EDAW, Inc. (2003). "North West Mexico Marine Market Analysis, report for the Packard Foundation." Menlo Park.

Estado de Baja. (2003). "Serie Historica de la Produccion Pesquera." http://www.sfa.gov.mx/estadistica/pesca/97-02.pdf

Fernandez, L. (2002). "Maritime Trade and Migratory Species Management to Protect Biodiversity," Environmental and Resource Economics, forthcoming.

Fisheries and Oceans Canada. (2002). "Summary of Canadian Commercial Catches, Fisheries Statistics, Fisheries and Oceans Canada." Ottawa.

Fofonoff, P., G. Ruiz, B. Steves, J. Carlton. (2003). "In Ships or on Ships? Mechanisms of Transfer and Invasion for Nonnative Species to the Coasts of North America." Chapter 7 in G. Ruiz and J. Carlton, eds. Invasive Species Vectors and Management Strategies, Island Press, Wash.D.C.

Forster, B. (1973). "Optimal Consumption Planning in a Polluted Environment," Economic Records, 49.

General Accounting Office (GAO). (2002). "Invasive Species Clearer Focus and Greater Commitment Needed to Effectively Manage the Problem." GAO Report No. -03-1, Wash. D.C.

Hanemann,M. (2003). "The Economic Value of Beach Recreation in Southern California." presentation for Economics and Water Quality Management Workshop, University of Southern California, February 17, 2003.

Hanemann, W. and I. Strand. (1993). "Natural Resource Damage Assessment: Economic Implications for Fisheries Management." *American Journal of Agricultural Economics* 75.

Hayes, K. and C. Sliwa. (2003). "Identifying Potential Marine Pests- A Deductive Approach Applied to Australia." *Marine Pollution Bulletin* 46, 91-98.

Horan, R., J. Shortle, and D. Abler. (1998), "Ambient Taxes When Polluters have Multiple Choices," in *Journal of Environmental Economics and Management*, 36, 186-199.

Horan, R., C. Perrings, F. Lupi, and C. Bulte. (2002). "Biological Pollution Prevention Strategies under Ignorance: The Case of Invasive Species," *American Journal of Agricultural Economics*, 84(5):1303-1310.

Horan, R., J. Shortle, and D. Abler. (2002). "Ambient Taxes Under m-Dimensional Choice Sets, Heterogeneous Expectations and Risk Aversion, *Environmental and Resource Economics*, 21(2):189-202.

International Maritime Organization (IMO). (2002). "International Ship and Port Facility Security (ISPS) Code." Conference of Contracting Governments to the International Convention for the Safety of Life at Sea, London.

International Maritime Organization (IMO). (2004). "Ballast Water and Solids Numerical Limit." Conference of Contracting Governments to the Convention for the Safety of Life at Sea, London.

Johnson, L. and J. Miller. (2002). "What You Need to Know about Nontoxic Antifouling Strategies for Boats." UC Sea Grant Report No. T-049, San Diego.

Kolstad, C., T. Ulen, and G. Johnson. (1990). "Ex Ante Regulation Vs. Ex Post Liability for Harm: Substitutes or Complements?" *American Economic Review* 80.

Kolstad, C. (2000). Environmental Economics, Oxford University Press, Oxford.

Llacer, F. (2004). "Open Registers: Past, Present, and Future," Marine Policy, 27:513-523.

Levings, C., J. Cordell, S. Ong, and G. Piercey. (2004). “The origin and identification of invertebrate organisms being transported to Canada’s Pacific coast by ballast water.” *Canadian Journal of Fisheries* 61(1).

Lloyd’s Register World Fleet Statistical Tables (2002) Lloyd’s, London.

Lynch, L. (2002). “Migration of Exotic Pests: Phytosanitary Regulations and Cooperative Policies to Protect U.S. Ecosystems and Agricultural Interests.” in L. Fernandez and R. Carson (eds.) Both Sides of the Border: Transboundary Environmental Management Issues Facing Mexico and the United States, Kluwer Academic Publishers, Dordrecht.

Milne, A. (1990). “Roughness and Drag from the Marine Chemist’s Viewpoint.” Proceedings of the International Workshop on Marine Roughness and Drag. Royal Institution of Naval Architects, London.

Olson, L. (2002). “The Economics of Controllling a Stochastic Biological Invasion.” *American Journal of Agricultural Economics* 84(5).

PACFIN (Pacific Fisheries Information Network), Data of Shellfish Market and associated Wetfish Market, Pacific States Marine Fisheries Commission, Gladstone.(trends from 1990s through 2004).

Perrings, C. (2002). “Biological Invasions in Aquatic Systems: The Economic Problem.” *Bulletin of Marine Science* 70(2), 541-552.

Pimental, D., R, Zuniga and D. Morrison. (2000). “Update on the Environmental and Economic Costs Associated with Alien-Invasive Species in the United States.” *Ecological Economics.* In press.

Rigby, G. and A. Taylor. (2001). “Ballast Water Treatment to Minimize the Risks of Introducing Nonindigenous Marine Organisms in to Australian Ports.” Ballast Water Report Series No. 13, Prepared for the Department of Agriculture Fisheries and Forestry.

Ruiz, G. and J. Carlton. (2003). “Invasive Species Vectors and Management Strategies.” Island Press, Wash. D.C.

Segerson, K. (1988). “Uncertainty and Incentives for Nonpoint Pollution Control,” *Journal of Environmental Economics and Management*, 15:87-98.

Segerson, K. (1995). “Liability and Penalty Structures in Policy Design.” Chapter 13 in The Handbook of Environmental Econoimics, D. Bromley, ed, Basil Blackwell Ltd, Cambridge.

Tamburri, M., K. Wasson, and M Matsuda. (2002). “Ballast Water Deoxygenation can Prevent Aquatic Introductions While Reducing Ship Corrosion.” *Biological Conservation* 103.

Taylor, A., G. Rigby, S. Gollasch, M. Voigt, G. Hallegraeff, T. McCollin, and A Jelmert. (2002). "Preventative Treatment and Control Techniques for Ballast Water." in Invasive Aquatic Species of Europe: Distributions, Impacts, and Management, E. Leppakoski, S. Gollasch, and S. Olenin, (eds.) Kluwer Academic Publishers, Dordrecht.

United States Coast Guard. (2004). Shipboard Technology Evaluation Program (STEP): Experimental Ballast Water Treatment Systems, Coast Guard Navigation and Vessel Inspection Circular, Vol. 1/04.

U.S. Commission on Ocean Policy. (2004). "Preliminary Report of the U.S. Commission on Ocean Policy-Governors' Draft." Wash.D.C., April 2004.

U.S. Maritime Administration. (2001). 2000-2002 Waterborne Traffic Statistics, website: http://www.marad.dot.gov/MARAD_statistics/index.html

Wilcove, D. D. Rothstein, J. Dubow, A. Phillips, and E. Losos. (1998). "Quantifying Threats to Imperiled Species in the United States." *Bioscience* 48.

Zentner, J., J. Glaspy, and D. Schenk. (2003). "Wetland and Riparian Woodland Restoration Costs." *Ecological Restoration* 21(3), 166-173.

Appendix 1

Verifying that Lump-sum Subsidy S Ensures $\alpha_r = \alpha_t$

It is assumed above that lump-sum subsidy S ensures $\alpha_r = \alpha_t$.

To verify this assumption holds under the incentive mechanism and that the profit-maximizing shipper will report α_r equal to α_t, it is sufficient to show that the shipper cannot increase profits by changing its reported value α from α_t to some other value α_r; that is, it is sufficient to show that

(A.1) $$\left.\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_r}\right|_{\alpha_r=\alpha_t} = 0 \cdot$$

Substituting $\frac{\partial s}{\partial \alpha_r} = M_1$, $\frac{\partial \overline{X}_1}{\partial s} = \frac{1}{2\alpha_t (a_1/a_2)^2 (1/\lambda)}$,

$$\frac{\partial S(\alpha_r)}{\partial \alpha_r} = c_1 \frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - \frac{\partial s}{\partial \alpha_r}\overline{B}_1 - s\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - c_2\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2}\right)\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r}$$

$$+ 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{r_1}{r_2}\right)^2 \overline{X}_1 \frac{\partial \overline{X}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} + \left(\frac{1}{\lambda}\right)\left(\left(\frac{\bar{I}}{r_2}\right) - \left(\frac{r_1}{r_2}\right)\overline{X}_1\right)^2 - \frac{B_1^2}{4\left(\frac{r_1}{r_2}\right)^2\left(\frac{1}{\lambda}\right)},$$

and the expressions for M_1, M_2, M_3, and $\overline{B}_1$ into equation (17), yields:

$$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_r} = \int_0^\infty \left[2\alpha_t D\left(\frac{\bar{I}}{a_2}\right)\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - 2\alpha_t D\left(\frac{a_1}{a_2}\right)^2 \overline{B}_1 \frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2}\right)\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r}\right.$$

$$\left. + 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{a_1}{a_2}\right)^2 \overline{B}_1 \frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r}\right]\cdot\left(\lambda e^{-\lambda D}\right) \equiv 0 \cdot$$

Carrying-out integration (via the methods of u-substitution and integration by parts),

$$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_r} = 2\alpha_t\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2}\right)\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - 2\alpha_t\left(\frac{1}{\lambda}\right)\left(\frac{a_1}{a_2}\right)^2 \overline{B}_1 \frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r} - 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{\bar{I}}{a_2}\right)\left(\frac{a_1}{a_2}\right)\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_r}$$

$$+ 2\alpha_r\left(\frac{1}{\lambda}\right)\left(\frac{a_1}{a_2}\right)^2 \overline{B}_1 \frac{\partial\overline{B}_1}{\partial s}\frac{\partial s}{\partial\alpha_r} \equiv 0 .$$

Evaluating the last expression above for $\alpha_r = \alpha_t$ verifies that $\left.\frac{\partial E(\pi(\overline{B}_1))}{\partial\alpha_r}\right|_{\alpha_r=\alpha_t} = 0$. In this way, the incentive is viewed as incentive compatible and individually rational for the shipper.

Appendix 2

Verifying that Lump-sum Fee F Ensures $\alpha_r = \alpha_t$

It is assumed above that lump-sum fee F ensures $\alpha_r = \alpha_t$.

To verify that the profit-maximizing shipper will report α_r equal to α_t, it is sufficient to show that the shipper cannot increase profits by changing its reported value α from α_t to some other value α_r; that is, it is sufficient to show:

(A.2) $$\left.\frac{\partial E(\pi(\dddot{B}_2))}{\partial\alpha_r}\right|_{\alpha_r=\alpha_t} = 0 .$$

Substituting $\frac{\partial t}{\partial\alpha_r} = -M_4$, $\frac{\partial\dddot{B}_2}{\partial t} = \frac{-1}{2\alpha_t(1/\lambda)}$, $\frac{\partial F(\alpha_r)}{\partial\alpha_r} = c_1\left(\frac{a_2}{a_1}\right)\frac{\partial\dddot{B}_2}{\partial t}\frac{\partial t}{\partial\alpha_r} - c_2\frac{\partial\dddot{B}_2}{\partial t}\frac{\partial t}{\partial\alpha_r}$ $- \frac{\partial t}{\partial\alpha_r}\dddot{B}_2 - t\frac{\partial\dddot{B}_2}{\partial t}\frac{\partial t}{\partial\alpha_r} - \left(\frac{1}{\lambda}\right)\dddot{B}_2^2 - 2\alpha_r\left(\frac{1}{\lambda}\right)\dddot{B}_2\frac{\partial\dddot{B}_2}{\partial t}\frac{\partial t}{\partial\alpha_r} + \frac{M_4^2}{4(1/\lambda)}$, and the expressions for M_4 and $\dddot{B}_2$ into equation (33) and evaluating the integral, yields:

$$\frac{\partial E(\pi(\dddot{B}_2))}{\partial\alpha_r} = -\frac{2\alpha_r^2 M_4^2}{4\alpha_t\alpha_r(1/\lambda)} + \frac{2\alpha_r^2 M_4^2}{4\alpha_t^2(1/\lambda)} - \frac{\alpha_t^2 M_4^2}{4\alpha_t^2(1/\lambda)} + \frac{\alpha_r^2 M_4^2}{4\alpha_t^2(1/\lambda)} \equiv 0 .$$

By setting $\alpha_r = \alpha_t$, the shipper satisfies its profit-maximizing condition $\frac{\partial E(\pi(\dddot{B}_2))}{\partial\alpha_r} \equiv 0$.

Table 1. Model notation.

π = shipper profits per cubic meter

r = firm profits per cubic meter in the absence of IMO standard costs

B_1 = cubic meters of ballast water

B_2 = cubic meters of biofouling

c_1 = per-cubic meter of ballast water

c_2 = per-cubic meter of biofouling

$\bar{I}$ = IMO standard constraint

a_1 = engineering parameter (per-unit contribution of B_1 toward satisfying $\bar{I}$)

a_2 = engineering parameter (per-unit contribution of B_2 toward satisfying $\bar{I}$)

s = subsidy paid by port to shipper per cubic meter

S = lump sum subsidy paid by port to shipper

α_t = shipper's true liability share of invasive species damage costs

α_r = shipper's reported liability share of invasive species damage costs

D = invasive species damage severity index, a random variable

p(D) = probability density function of random variable D

λ = location parameter of exponential probability density function

$M_1 \equiv c_2(a_1/a_2) - c_1$, a derived model parameter

$M_2 \equiv 2D(\bar{I}/a_2)(a_1/a_2)$, a derived model parameter

$M_3 \equiv D(a_1/a_2)^2$, a derived model parameter

$M_4 \equiv c_1 a_2/a_1 - c_2$, a derived model parameter

Table 2. Solution values for the multiple externality model, under a subsidy-based incentive mechanism.

Panel a.--Subsidy values, s*, S*

	α_r 0.5	α_r 0.75	α_r 0.99
s*	0.541316	0.270658	0.010826
S*	0.022046	0.033069	0.043651

Panel b.—Ballast Water, $\overline{B}_1$

α_t \ α_r	0.5	0.75	0.99
0.5	4.0727	4.0257	3.9806
0.75	4.1040	4.0727	4.0426
0.99	4.1192	4.0955	4.0727

Panel c.-Biofouling, $\overline{B}_2$

α_t \ α_r	0.5	0.75	0.99
0.5	1.781	2.671	3.526
0.75	1.187	1.781	2.350
0.99	0.899	1.349	1.781

Panel d.—Shipper's expected profit, $\mathrm{E}(\pi)$, per cubic meter

α_t \ α_r	0.5	0.75	0.99
0.5	0.224272	0.224272	0.224272
0.75	0.224145	0.224145	0.224145
0.99	0.224023	0.224023	0.224023

Panel e.—Expected social welfare, $\mathrm{E}(\mathrm{W})$, per cubic meter

α_t \ α_r	0.5	0.75	0.99
0.5	0.179925	0.179798	0.179437
0.75	0.179869	0.179925	0.179873
0.99	0.179801	0.179895	0.179925

Model parameter values: $r = 0.27$, $c_1 = \$2.39$, $c_2 = \$0.07$, $a_1 = 0.36$, $a_2 = 0.19$, $\overline{I} = 0.01$, $B_2^0 = 0.11$ and $\lambda = 0.012$.

Table 3. Solution values for the multiple externality model, under a tax-based incentive mechanism.

Panel a.--Tax and Fee values, t*, F*

	α_r 0.5	0.75	0.99
t*	0.285694	0.142847	0.005714
F*	0.000509	0.000763	0.001007

Panel b.—Ballast Water, $\overline{B}_1$

α_t	α_r 0.5	0.75	0.99
0.5	4.0727	4.0257	3.9806
0.75	4.1040	4.0727	4.0426
0.99	4.1192	4.0955	4.0727

Panel c.-Biofouling, $\overline{B}_2$

α_t	α_r 0.5	0.75	0.99
0.5	1.781	2.671	3.526
0.75	1.187	1.781	2.350
0.99	0.899	1.349	1.781

Panel d.—Shipper's expected profit, $\mathrm{E}(\pi)$, per cubic meter

α_t	α_r 0.5	0.75	0.99
0.5	0.179162	0.179162	0.179162
0.75	0.179035	0.179035	0.179035
0.99	0.178913	0.178913	0.178913

Panel e.—Expected social welfare, $\mathrm{E}(\mathrm{W})$, per cubic meter

α_t	α_r 0.5	0.75	0.99
0.5	0.179925	0.179798	0.179437
0.75	0.179869	0.179925	0.179873
0.99	0.179801	0.179895	0.179925

Model parameter values: r = 0.27, c_1 = \$2.39, c_2 = \$0.07, a_1 = 0.36, a_2 = 0.19, $\overline{I}$ = 0.01, B_2^0 = 0.11 and λ = 0.012 .