Valuation for Environmental Policy: Ecological Benefits

A Workshop sponsored by U.S. Environmental Protection Agency's National Center for Environmental Economics (NCEE) and National Center for Environmental Research (NCER)

Crowne Plaza Washington National Airport Hotel
1480 Crystal Drive
Arlington, VA 22202

April 23-24, 2007

Disclaimer

U.S. Environmental Protection Agency (EPA)
National Center for Environmental Economics (NCEE) and
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Agenda

April 23, 2007: Valuation for Environmental Policy

8:00 a.m. – 8:30 a.m.	**Registration**	
8:30 a.m. – 8:45 a.m.	**Introductory Remarks** Rick Linthurst, National Program Director for Ecology, EPA, Office of Research and Development	
8:45 a.m. – 11:30 a.m.	**Session I: Benefits Transfer** Session Moderator: Steve Newbold, EPA, NCEE	
	8:45 a.m. – 9:15 a.m.	Benefits Transfer of a Third Kind: An Examination of Structural Benefits Transfer George Van Houtven, Subhrendu Pattanayak, Sumeet Patil, and Brooks Depro, Research Triangle Institute
	9:15 a.m. – 9:45 a.m.	The Stability of Values for Ecosystem Services: Tools for Evaluating the Potential for Benefits Transfers John Hoehn, Michael Kaplowitz, and Frank Lupi, Michigan State University
9:45 a.m. – 10:00 a.m.	**Break**	
	10:00 a.m. – 10:30 a.m.	Meta-Regression and Benefit Transfer: Data Space, Model Space and the Quest for ‘Optimal Scope’ Klaus Moeltner, University of Nevada, Reno, and Randall Rosenberger, Oregon State University
	10:30 a.m. – 10:45 a.m.	Discussant: Matt Massey, EPA, NCEE
	10:45 a.m. – 11:00 a.m.	Discussant: Kevin Boyle, Virginia Tech University
	11:00 a.m. – 11:30 a.m.	Questions and Discussion
11:30 a.m. – 12:45 p.m.	**Lunch**	

April 23, 2007 (continued)

12:45 p.m. – 3:30 p.m.	**Session II: Wetlands and Coastal Resources** Session Moderator: Cynthia Morgan, EPA, NCEE		
	12:45 p.m. – 1:15 p.m.	A Combined Conjoint-Travel Cost Demand Model for Measuring the Impact of Erosion and Erosion Control Programs on Beach Recreation Ju-Chin Huang, University of New Hampshire; George Parsons, University of Delaware; Min Qiang Zhao, The Ohio State University; and P. Joan Poor, St. Mary's College of Maryland	
	1:15 p.m. – 1:45 p.m.	A Consistent Framework for Valuation of Wetland Ecosystem Services Using Discrete Choice Methods David Scrogin, Walter Milon, and John Weishampel, University of Central Florida	
1:45 p.m. – 2:00 p.m.	**Break**		
	2:00 p.m. – 2:30 p.m.	Linking Recreation Demand and Willingness To Pay With the Inclusive Value: Valuation of Saginaw Bay Coastal Marsh John Whitehead and Pete Groothuis, Appalachian State University	
	2:30 p.m. – 2:45 p.m.	Discussant: Jamal Kadri, EPA, Office of Wetlands, Oceans, and Watersheds	
	2:45 p.m. – 3:00 p.m.	Discussant: John Horowitz, University of Maryland	
	3:00 p.m. – 3:30 p.m.	Questions and Discussion	
3:30 p.m. – 3:45 p.m.	**Break**		
3:45 p.m. – 5:45 p.m.	**Session III: Invasive Species** Session Moderator: Maggie Miller, EPA, NCEE		
	3:45 p.m. – 4:15 p.m.	Models of Spatial and Intertemporal Invasive Species Management Brooks Kaiser, Gettysburg College, and Kimberly Burnett, University of Hawaii at Manoa	
	4:15 p.m. – 4:45 p.m.	Policies for the Game of Global Marine Invasive Species Pollution Linda Fernandez, University of California at Riverside	
	4:45 p.m. – 5:00 p.m.	Discussant: Marilyn Katz, EPA, Office of Wetlands, Oceans, and Watersheds	
	5:00 p.m. – 5:15 p.m.	Discussant: Lars Olsen, University of Maryland	
	5:15 p.m. – 5:45 p.m.	Questions and Discussion	
5:45 p.m.	**Adjournment**		

April 24, 2007: Valuation for Environmental Policy

8:30 a.m. – 9:00 a.m.	**Registration**	
9:00 a.m. – 11:45 a.m.	**Session IV: Valuation of Ecological Effects** Session Moderator: William Wheeler, EPA, NCER	
	9:00 a.m. – 9:30 a.m.	Integrated Modeling and Ecological Valuation: Applications in the Semi Arid Southwest David Brookshire, University of New Mexico, Arriana Brand, Jennifer Thacher, Mark Dixon,Julie Stromberg, Kevin Lansey, David Goodrich, Molly McIntosh, Jake Gradny, Steve Stewart, Craig Broadbent and German Izon
	9:30 a.m. – 10:00 a.m.	Contingent Valuation Surveys to Monetize the Benefits of Risk Reductions Across Ecological and Developmental Endpoints Katherine von Stackelberg and James Hammitt, Harvard School of Public Health
10:00 a.m. – 10:15 a.m.	**Break**	
	10:15 a.m. – 10:45 a.m.	Valuing the Ecological Effects of Acidification: Mapping the Extent of Market and Extent of Resource in the Southern Appalachians Shalini Vajjhala, Anne Mische John, and David Evans, Resources for the Future
	10:45 a.m. – 11:00 a.m.	Discussant: Joel Corona, EPA, Office of Water
	11:00 a.m. – 11:15 a.m.	Discussant: David Simpson, Johns Hopkins University
	11:15 a.m. – 11:45 a.m.	Questions and Discussion
11:45 a.m. – 1:00 p.m.	**Lunch**	
1:00 p.m. – 4:15 p.m.	**Session V: Water Resources** Session Moderator: Adam Daigneault, EPA, NCEE	
	1:00 p.m. – 1:30 p.m.	Valuing Water Quality as a Function of Physical Measures Kevin Egan, Joe Herriges, John Downing, and Katherine Cling, Iowa State University
	1:30 p.m. – 2:00 p.m.	Cost-Effective Provision of Ecosystem Services from Riparian Buffer Zones Jo Albers, Oregon State University; David Simpson, Johns Hopkins University; and Steve Newbold, NCEE
2:00 p.m. – 2:15 p.m.	**Break**	
	2:15 p.m. – 2:45 p.m.	Development of Bioindicator-Based Stated Preference Valuation for Aquatic Resources Robert Johnston, Eric Shultz, Kathleen Segerson, Jessica Kukielka, Deepak Joglekar, University of Connecticut; and Elena Y. Besedin, Abt Associates

April 24, 2007 (continued)

	2:45 p.m. – 3:05 p.m.	Comparing Management Options and Valuing Environmental Improvements in a Recreational Fishery Steve Newbold and Matt Massey, NCEE
	3:05 p.m. – 3:20 p.m.	Discussant: Julie Hewitt, EPA, Office of Water
	3:20 p.m. – 3:35 p.m.	Discussant: George Parsons, University of Delaware
	3:35 p.m. – 4:05 p.m.	Questions and Discussions
4:05 p.m. – 4:15 p.m.	**Final Remarks**	
4:15 p.m.	**Adjournment**	

Models of Spatial and Intertemporal Invasive Species Management

Kimberly M. Burnett, University of Hawaii, Manoa
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1. Introduction

Damages from invasive species are spatially and intertemporally variable. We define invasive species as those which have negative net benefits to society when introduced to an area in which they are non-native.[1] Valuation of these damages is often the first uncertain step in determining policy responses to invasive species problems.

As an invasive species spreads and increases in density across a landscape over time, the costs of locating and controlling it also change. Human intervention must therefore be spatially and temporally sensitive if it is to achieve the goal of minimizing net losses from the spread of invasive species. The three main, interdependent policy interventions are prevention, early detection and rapid response (EDRR), and control.

For clear guidance on optimal responses, all three policies require information on the likelihood of arrivals and establishment or re-establishment of an invasion, expected growth (spread), control costs, and expected damages. This is due to the recursive nature of the problem; spending large amounts of money to prevent a species that can be cheaply controlled at levels where it causes little actual damage if it establishes is a waste, while spending large amounts of money to control for a species that is likely to re-invade without integrated prevention decisions may also be a waste. Unfortunately, due in part to this recursivity but also due to the generally nonlinear nature of biological growth and spread, analytical solutions to a fully integrated, spatially and temporally explicit prevention and control problem even for a single species are generally intractable (see Smith et al. 2007, Burnett 2007).

Numerical solutions, with caveats and assumptions about transference of biological growth, expected costs, and damages from other locales, are possible for species with sufficient information about these parameters and the likelihood of invasion. A small but growing set of such case studies is evolving both in the economics and the ecological literatures, though few to date tackle both spatial and temporal issues together (Rejmanek and Richardson 1996, With 2002, Eiswerth and Johnson 2002, Burnett et al. 2006, Kaiser and Burnett 2007, Burnett et al. 2007). Certain locations encourage and facilitate analysis; the Hawaiian islands, the Cape of

[1] Many introductions are purposeful as they convey anticipated net benefits for those responsible for the introductions; in these cases there is the additional complication of unaligned incentives and distributional considerations in policy. We abstract from these considerations here, but mention them to highlight the fact that many of the consequences of invasive species are inflicted upon ecosystems (and their ecological benefits) rather than markets.

South Africa, Australia, and New Zealand, for example, all have fragile, isolated ecosystems where the rate of change in species introduction has rapidly increased with increased global integration over the past 400 (or fewer) years. These locations generate valuable benefits from biodiversity and are also, as they try to develop diversified global economies supporting growing populations and/or tourism, dependent on ecosystems for services like water quantity and quality, agricultural production, and aesthetics or other environmental factors that create a general satisfaction with life.

Due to the visible and significant threats these localities face, they are understandably at the forefront of efforts to manage invasive species problems. We focus on the Hawaiian Islands as a representation of the broader threat because in Hawaii the full problem, from establishment to eradication and back again, is writ large. We present three cases, described below, as analyzed independently in previous research, and draw comparisons and generalizations as possible from them.

First, we focus on measuring damages from an invasive species. This analysis does not inform policy decisions regarding prevention, EDRR, or control directly. Rather it demonstrates the first step in determining the expected damages. We examine the costs from frogs (*Eleutherodactylus coqui*) on the Big Island in Hawaii in terms of noise pollution effects on property values (Kaiser and Burnett 2006). We recap it and add it to the discussion here because it captures an essential consideration for ecosystem valuation and the threat from invasive species. In the words of Joni Mitchell: "you don't know what you've got till it's gone." The ability to value the anticipated losses from the frog depends on the losses that have already occurred due to the early stages of the invasion.

Second, we investigate optimal EDRR of a species with a possible, currently undetected, presence, the brown treesnake (*Boiga irregularis*) (Kaiser and Burnett 2007). Significant economic and ecological damages are anticipated from the snake's presence in Hawaii. The snake threatens some of the same ecosystem benefits as the tree (biodiversity) as well as the power supply and human health. Several specimens have been intercepted between Guam and Hawaii in the past 20 years, and it is possible that others have gone undetected. The appropriate policy tool in this case, EDRR, is explicitly spatial, as the searches, and their costs, are location specific.

Third, we investigate optimal control of a species with a limited presence already, the shrubby tree miconia (*Miconia calvescens*) (Burnett et al. 2007). Significant ecological damages are anticipated from the continued spread of the tree. Some of these damages have market connections, in particular ground water quantity, while others do not, in particular biodiversity.

From these three cases, we cull findings on the sensitivity of policy decisions to the parameters of import outlined above, namely arrivals, biological growth, control costs, and damages.

2. Case Studies

2.1 Coqui Frogs

Eleutherodactylus coqui, a small frog native to Puerto Rico, was introduced to Hawaii in the late 1980s, presumably as a hitchhiker on plant material from the Caribbean or Florida.. The frogs are present on the four main islands of Kauai, Oahu, Maui, and the island of Hawaii, although the populations are limited to specific areas on each island.

The primary economic effect of the frog is noise pollution. The combined lack of predation and competition for resources has resulted in densities reaching 55,000 frogs per hectare,[2] more than double the highest densities in the frog's native Puerto Rico (Beard and Pitt 2005). The males' calls, which are individually between 80-90 dBA at 0.5 m, now extend from an hour before sunset until dawn. The Hawaii Department of Health sets the threshold for minimizing impacts to human health and welfare at only 70 dBA (Department of Health, Hawaii Revised Statutes Section 324F-1). We concentrate on elucidating these damages through changes in property values. Economic theory suggests that property values for locations with noise pollution should be lower than comparable properties without. Since the frog's calls reach approximately 500 to 800 meters, we investigate whether properties within this range of a registered coqui complaint trade at lower prices than those beyond that perimeter.

We use a standard hedonic pricing model to evaluate the effect of registered coqui complaints on property values. Using this theory and a of real estate transactions from 1995 to 2005 for Hawaii county, we consider that individuals buy and sell properties as bundles of characteristics: here, the relevant characteristics for the properties are proximity of frog complaints, district, acreage, year of transaction, presence of housing structures, broad zoning class, and finely gradated neighborhoods as defined by the tax authority.[3] Our reduced form price function is:

$$P_i = f(D_i, F5_i, F8_i, A_i, M_t, L_i, Y_i, Z_i, N_i), \quad (1)$$

Where Pi = natural log of sales price of transaction i,

D_i = district (Puna, South Hilo, North Hilo, Hamakua, North Kohala, South Kohala, North Kona, South Kona, Kau),

$F5_i$ = indicator variable for frog complaint within 500 m previous to sale,

$F8_i$ = indicator variable for frog complaint between 500-800 m previous to sale,

A_i= natural log of acres for property *i*,

M_t = natural log of average mortgage rate for month of transaction,

L_i = indicator variable for housing structures on property,

[2] Densities of up to 133,000 per ha have been recorded on the island of Hawaii.

[3] Ideally, we would wish to include housing stock to control for effects of changes in supply. Unfortunately, this data is not available. The best we can do is use this time trend to broadly capture such differences. The neighborhood variables also help control for supply shifts, however these cannot be isolated as instruments so a two-stage estimation procedure is not possible.

Y_i = year of transaction,
Z_i = zoning class (agriculture, apartment, unimproved residential, improved residential, conservation, industrial, resort, commercial)
N_i = tax assessor's neighborhood classification (1736 groupings).

We have data from the Hawaii County Tax Assessor's office on 50,033 real estate transactions and properties from 1995-2005, shown in Figure 1. We omit unvalidated sales and sales that fall within the lowest 1% or highest 1% of prices to eliminate outliers and pricing irregularities. This results in 37,228 properties, each of which changes hands between 1 and 6 times (average 1.2 times), for a total of 46,405 transactions.

Table 1. District Level Summary Statistics

District	Number of transactions	Mean Transaction Price ($) (standard error)	Mean fraction of properties within 500m of frog complaints (standard error)
Puna	20,914	25,912 (40,177)	0.17 (0.38)
South Hilo	4,163	99,130 (81,389)	0.37 (0.48)
North Hilo	412	128,321 (110,007)	0.00 (0)
Hamakua	683	123,091 (109,196)	0.02 (0.13)
North Kohala	1,452	179,028 (153,884)	0.01 (0.09)
South Kohala	4,595	197,095 (176,779)	0.21 (0.41)
North Kona	7,871	187,438 (150,954)	0.33 (0.47)
South Kona	1,427	124,315 (154,234)	0.14 (0.35)
Kau	5,049	23,362 (43,874)	0.00 (0.04)

We expect that frog complaints cause a greater reduction in property values the closer they are. Currently, we have frog complaints reported to USDA/APHIS or the Big Island Invasive Species Committee (BIISC) from 1997-2001. We use geographical information systems (GIS) software (ArcView) to match the verified frog complaints to property transactions, and generate indicator variables for whether a property is within 500m of a previous complaint and whether it is within 800m of a previous complaint. We then generate an indicator variable for whether a property is between 500-800m of a previous complaint. Incentives of both buyers and sellers are such that properties with frogs should trade at prices lower than properties without frogs, and our reduced form estimates include loss in value to sellers as well as the lower willingness to pay of buyers.

The remaining variables control for other characteristics of properties affecting their value, and more detailed discussion can be found in Kaiser and Burnett (2006).

Table 2 shows the results for the regression including all of the districts (neighborhood controls not reported). Note that Puna is the omitted district and agriculture is the omitted zoning, so that the interpretation of the dummy variables is relative to the constant term representing Puna agricultural land transactions. Since we have transformed the continuous variables into logs, the results of our analysis will estimate elasticities. Thus, a one percent change in acreage, for example, will generate an estimated percent change in price indicated by the coefficient in column 2, Table 2, or 0.43 percent.

Table 2. Regression Results (dependent variable: Log Price)

Variable	Coefficient	Standard error	P-value
Frog500m	-0.16	0.01	0.00
Frog800m	-0.12	0.01	0.00
Log Acres	0.43	0.02	0.00
S_hilo_acres	-0.12	0.04	0.00
N_Hilo_acres	-0.15	0.07	0.03
Hamakua_acres	-0.06	0.04	0.09
N_Kohala_acres	-0.08	0.03	0.01
S_Kohala_acres	-0.24	0.03	0.00
N_Kona_acres	-0.26	0.03	0.00
S_Kona_acres	-0.31	0.05	0.00
Kau_acres	0.17	0.07	0.02
Log mortgate rate	-0.45	0.04	0.00
Residential structure	1.27	0.01	0.00
Year of sale	0.07	0.00	0.00
Improved Residential	0.23	0.14	0.10
Apartment	0.31	0.17	0.07
Commercial	0.14	0.26	0.58
Industrial	1.98	0.17	0.00
Conservation	-0.19	0.20	0.34
Resort	0.32	0.19	0.09
Unimproved Residential	0.53	0.33	0.11
Constant	-139.57	4.51	0.00

From the table, we see that most variables have the expected sign and influence on price. Virtually all variables are significantly different than zero at the 99% level (P-value < 0.01) (Huber-White robust errors correcting for heteroskedasticity due to the wide variation across districts). The overall fit of the regression is quite good, with an R^2 of 0.86.

The net impacts are in general fairly small, with only the residential structure and industrial property indicators, in addition to some neighborhood indicators (not reported), generating impacts on price greater than 1%.

The presence of frogs, however, does have a significant negative impact on property values. For properties within 500 meters of a complaint, property values decline 0.16%, or about 1/3 as much as values decline from a 1% increase in mortgage rates (-0.45%). For properties within 800m but not within 500 meters, property values decline less severely, at 0.12%. This is about ¼ of the drop from a 1% increase in mortgage rates.

Thus we have an estimate of net marginal damages from the spatial spread of the frog as a function of the properties in an invaded location. We could use this estimate, with additional estimates of damages to the floriculture industry, in conjunction with estimates of the cost of spread and the costs of capture to generate control policies for the frog. Misaligned incentives and missing information hinder this analysis, however. The floriculture industry, for example, is reluctant to share information on the frog's effects on their business.[4] The spread of the frog has been much faster and at a higher density than its behavior in its native range would suggest and so it has been underestimated over the last fifteen years. Early control techniques (e.g. spray caffeine) resulted in significant external costs to ecosystem health and had to be abandoned; new techniques (e.g. direct application of hydrated lime) are costly and not as effective. Hand capture is often possible for individual males because they can be located by their call, but female frogs do not call and also are believed to spend the days in the forest canopy, making them difficult control targets.

There is some risk that the frog is reducing native arthropod populations, but the science regarding the extent of this possibility remains unclear, as the frogs exhibit quite generalist eating behavior. While some might argue that the damages from the frog are not communal and that the frog should be treated like any household pest, left to the individual owners to treat or not treat, large source populations exist on public land. Control of these populations as well as prevention of the spread of the frog to new areas is clearly within the scope of public policy. The rule of thumb for such invasions has generally been that the quicker one acts the lower the overall costs. We examine this belief by examining the cases of miconia and the Brown treesnake, below.

2.2 Brown Treesnake

In this section, we address EDRR as an explicitly spatial policy instrument using the case study of the Brown treesnake on the island of Oahu, Hawaii. The brown treesnake is another well known potential invader of Hawaii and much effort has been expended to study the potential effects of an invasion to Hawaii. (Savidge 1987, Fritts et al. 1987, 1990, 1994, Burnett et al, 2006, Burnett, 2007, Burnett et al, 2007). There have been eight brown treesnakes captured at the ports on the island of Oahu and hundreds of other sightings reported throughout the island. EDRR technology has been developed in the form of specially trained teams based throughout the Pacific who are immediately deployed following a credible sighting of a Brown treesnake on Oahu or on other at-risk islands. Two such deployments have occurred in Hawaii in the last two years, one on the island of Maui and the other on Oahu, although neither effort produced a snake.

Using Geographical Information Systems (GIS) software, we analyze spatially-explicit EDRR policies given the reality that prevention of the snake's entry may already have failed or will eventually fail at least one of the most likely entry points, regardless of budget (Burnett et al. 2006, Olson and Roy 2005). EDRR policies comprise of search and destroy activities that occur beyond incoming crafts at points of entry (prevention) to target removal of uncertain but likely specimens throughout the potential habitat range that have evaded detection. Intertemporal and spatial differences in policies are compared given varying assumptions about planning and management horizons and the arrival of the snake.

[4] The frog is transported in nursery stock and the risk of its presence lowers willingness to pay and the costs of selling un-infested plants, because they do not want to admit the presence of the frog and incur these losses.

We divide Oahu into a grid, but we use a finer subdivision for the case of the snake and each grid cell measures only 4 ha each. The choice of grid cell has potentially large effects that we discuss in section 3. Each cell is assigned initial properties that include currently existent data on likelihood of snake presence (distance from points of entry, proximity to roads[5]), resource assets at risk (bird habitat, presence of power transmission lines, human population density) and accessibility of treatment (proximity of roads and trails, slope, and land ownership).

From these initial conditions, we estimate expected snake populations for each cell across a thirty year period based on the likelihood of the presence of snakes, the expected marginal damages (per snake) as a function of the resources at risk and the marginal costs (per 4 ha area) as a function of accessibility and terrain.

Using this information, we build a spatial-intertemporal model that minimizes the expected net damages from the brown treesnake on Oahu. Since treatment decisions are EDRR search decisions, the unit of decision is the spatial cell rather than the snake population directly. Net expected damages are calculated for each cell by assuming that treatment clears an area of snakes for that time period, so that population-based damages are avoided.

The theoretical model is formalized as:

$$\min_{x_{it}} \sum_i \sum_{t=0}^{T} \beta^t \left(d_i \left(n_{it} \left(x_{it}, \sum_i x_{it} \right) \right) + C_i(x_{it}) \right) \tag{2}$$

$$n_{it} = n(r,t,x) = \frac{\sum_i x_{i,t-1}}{I} g(n_{t-1}, r) * (1 - x_{it}) \tag{3}$$

$$\sum_i C_{it} \le A_t \tag{4}$$

Where d_i is the expected damage for cell i, n_{it} is the population of the cell at time t as a function of own-cell (x_{it}) and other-cell (x_{jt}) EDRR treatments, C_i is the cost of EDRR for cell i, I is the total number of cells, g is the biological growth function which depends spatially on the distance from the expected start of the invasive population, β represents the discount factor, and A_t represents a temporally constrained appropriations budget for EDRR.

[5] We have more specific information about habitat than distance from points of entry, but after extended discussions with several Brown treesnake scientists it has become clear that the main limiting factor in Hawaii will be the availability of prey, for which we do not have specific densities. Fortunately for our analysis though unfortunately for avoiding the spread of the snake, the one point of agreement between all of the scientists on this matter is that they believe there exists sufficient prey base for snake expansion in all habitats present on Oahu for a population explosion comparable to the one on Guam after its arrival. Thus, since there exists no scientific evidence or theoretical model to credibly believe that forest habitat is more amenable than urban, for example, we accept that there will be abundant prey in every habitat and that differences for the snake will be minimal.

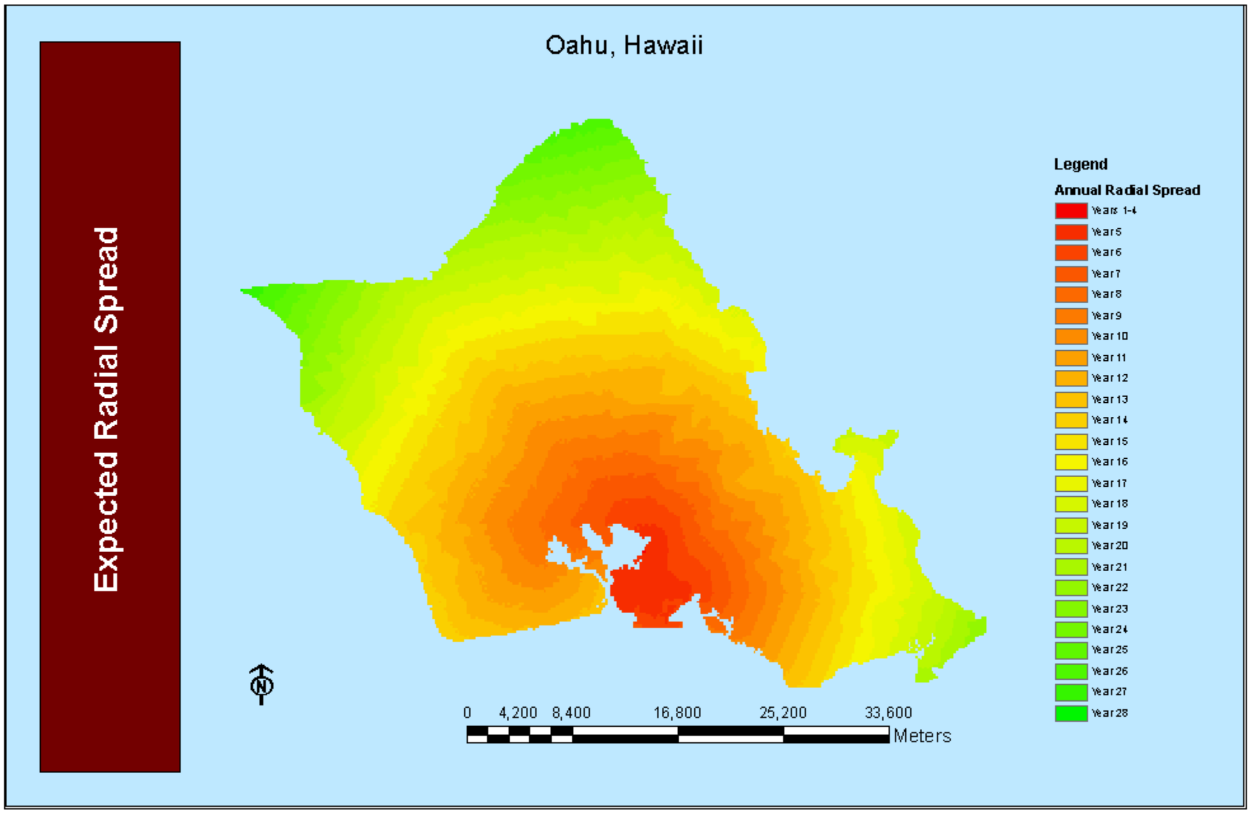
Spending C_i brings the population for period t to zero for an area, but invasion from other parts of the island, or anew from off-island, re-initiates growth in the next period. The larger the proportion of treated cells $\left(\frac{\sum_{i=1}^{I} x_{i,t-1}}{I}\right)$, the lower the rate of re-growth.

2.2.1 Snake Growth

The expansion path without intervention is based on the estimated expansion rate of 1.6 km/yr (Wiles et al. 2003) from the expected origins of the airport runways and Schofield facilities and the terrain through which the snakes must pass (Fig. 1d). Expected origins were weighted by capture experience on Oahu to date, with HNL being the most likely port of entry. Roads and trails are expected to provide the most rapid expansion paths (Timmins 2006); distance from roads and trails slows the radial spread.

Figure 1 illustrates the expected spread, with each change in color shade indicating another year's expansion of territory, from red to green. While there is a positive probability that the snake may appear in any cell at any time, the range is determined by the expected presence of at least one full snake.

Figure 1: Expected annual snake expansion



Note: Expected entry at Honolulu Airport (HNL) or the adjacent Hickam Air Force Base Airport (3/4 weight), Barber's Point Air Station (1/8 weight) or Schofield Barracks (1/8 weight)

Using the diffusion rate of 1.067 km^2/yr (Shigesada and Kawasaki 1997: 51), the average radii calculated from those illustrated in Figure 1, and the following expansion model, based on Fisher and Skellam (Shigesada and Kawasaki 1997), we determine the expected snake population in a given cell at a given time period. We assume the population changes as a function of both diffusion and internal growth:

$$\dot{n} = D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right) + \left(b - \mu n\right)n \qquad (5)$$

Where *n(x,y,t)* is population at time *t* in spatial coordinate *(x,y)* as measured from the original specimen's location, *D* is the diffusion rate, *b* is the intrinsic growth rate, $\mu \geq 0$ captures intraspecific competition, and *x* and *y* are spatial coordinates, and the radial distance, *r*, is determined by $r^2 = x^2 + y^2$. The first term captures the rate of spread, the second captures population growth within the given coordinates. We estimate from maximum densities experienced on Guam that the maximum snake carrying capacity in any cell (*K*) is 200 snakes.

Because there is no explicit solution to this non-linear problem, in order to create a tractable model that incorporates both spread and internal growth, we use the solution to the Skellam model for exponential growth and spread until the population of the cell reaches the point where it diverges significantly from a logistic growth function with a capacity of 200 snakes, which occurs at approximately 40 snakes. From that point, we use a logistic growth function to determine population in an area. We do not simply use the logistic function because it does not allow for radial spread to and from other cells.

Assuming an initial distribution where n_0 individuals invade the origin at t=0, we have untreated populations

$$n(r,t) = \frac{n_0}{4\pi Dt} \exp\left(bt - \frac{r^2}{4Dt} \right), \tag{6}$$

until $n(r,t) \geq 40$. After this point,

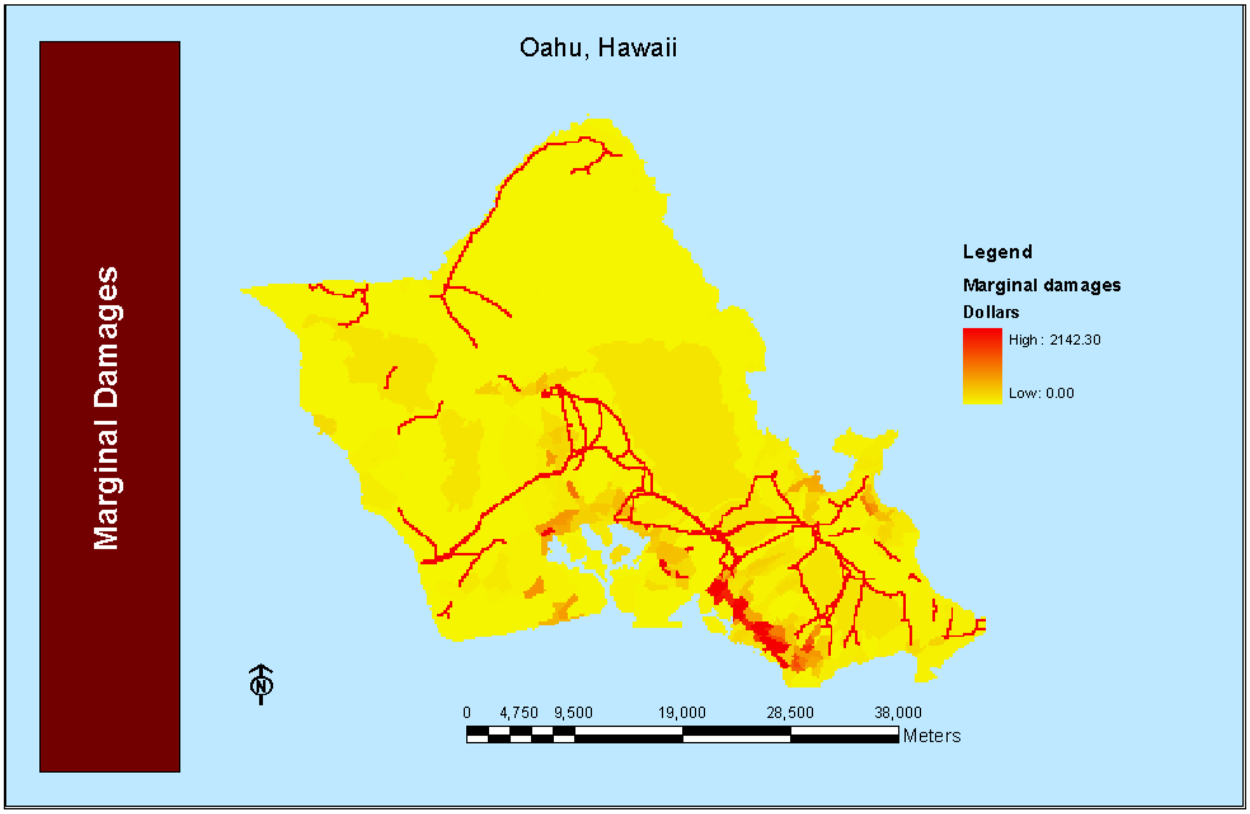
$$n(r,t) = n_r \left(\frac{Ke^{bt}}{K + n_r (e^{bt} - 1)} \right), \tag{7}$$

where n_r is the population (here, 40) when the growth function changes.

2.3.2 Damages

Figure 2 illustrates the range of damages across Oahu. Damages are calculated using a per snake linear coefficient that varies from a minimum of \$0 and a maximum of \$2143 (Fig. 2). Damages consist of three potential impacts: power outages, medical costs and human-snake interactions, and biodiversity losses. Details are available in Kaiser and Burnett 2007.

Figure 2: Total Damages



2.3.3 Snake Control Costs

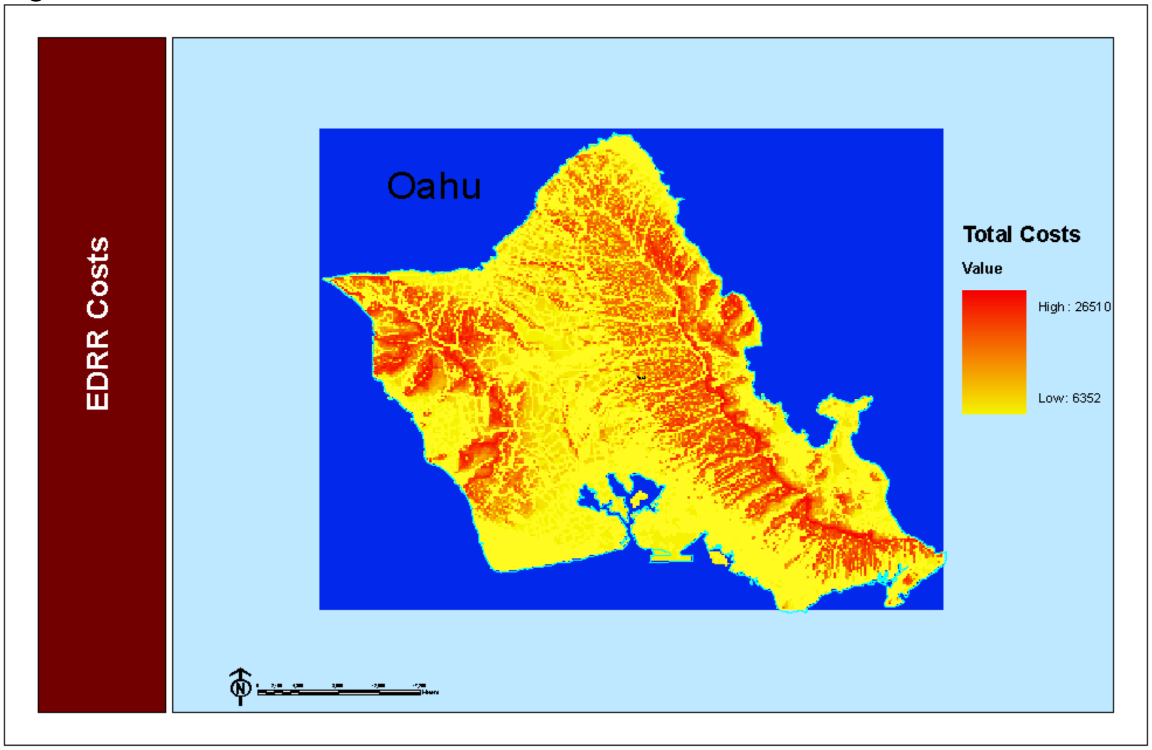
As discussed, a particular distinction between EDRR and other discussions of invasive species control is that with EDRR it is not known with certainty that there exists a population, while with control one generally assumes one can “harvest” a known population of the invasive species. Costs are therefore allocated spatially rather than as a function of population.

We describe EDRR treatment as consisting of preventative search, trapping and hand-removal (the only way to currently remove snakes too small to be trapped). Costs vary with terrain. Records on the costs of clearing an enclosed 5 ha plot on Guam (Rodda, personal communication) provide a least cost estimate of removing snakes from an area. Costs are scaled up from this base cost of $6,352 per 4 ha cell to account for slope of the terrain and distance from a road. The steeper the grade, the more energy required to search the area. Since the cost of searching is a labor cost, we use a model of the American College of Sports Medicine to translate grade into energy expenditure, and then increase costs proportionally to the increase in effort. The energy expenditure rate (EER) is estimated to be:

$$EER = 0.1v + 1.8v \cdot a + 3.5 \qquad (8)$$

Where v is the speed of walking and a is the percent grade (Sabatini et al. 2004). We assume a constant slow rate of walking at 0.5 km/hour to accommodate searching (Rodda, personal communication, Lardner, personal communication). Average slope for each cell is calculated from hillshade projections of Oahu in ArcGIS 9.1. Figure 3 illustrates total costs.

Figure 3: Snake Control Costs



For each cell, we first calculate the energy expenditure rate, EER. We then generate an energy expenditure ratio where we divide the cell's EER by the EER when the slope is zero, which provides an estimate of how much more difficult clearing the cell is than clearing the 5 ha test plot (which was on level ground) cost. This ratio is therefore multiplied by the base cost of $6352.[6]

Costs also increase with the distance of the cell needing treatment from accessible roads. We use analogous methodology to determine distance costs from roads by using ArcView Spatial Analyst to calculate the least cost distance path. First, based on the EER from the nearest road to the cell, we determine the least cost EER path from the nearest road to the cell. Then we create a ratio of this distance cost to the linear distance from the road. We then multiply this ratio by the labor cost of reaching the cell, estimated at $60 per unit. The maximum access cost is approximately $3420, while the average is approximately $540. The total cell cost is then the sum of the in-cell treatment cost and the distance (access) cost.[7]

[6] The maximum cost for thoroughly searching a cell for EDRR purposes using this formula is approximately $27,500, while the average cost is $11,700.

[7] Note this does not allow for treatment in multiple adjacent cells at discounted distance cost. However, since this method also assumes only one treatment time necessary (rather than repeated nights of search) the net effect is unclear. We leave this for later modeling. We also delay modeling of any external cost to accessing private land. One possibility is to assume that gaining access to private land and/or convincing private landowners to engage in search activities themselves is one of the main purposes of awareness campaigns, and that expenditures targeting awareness of a species can be considered additional costs of treating private land. In the case of the Brown treesnake in Oahu, this amounts to only about $3 per cell of private land, thus we have ignored this cost for now.

2.3.4 Snake Results

Currently, no known snake populations exist on Oahu, but there is general agreement amongst the scientific community that there may be between 0 and 100. We begin our analysis with $n_0=1$.[8] Thus, our initial application is for search only. Current search on Oahu occurs only after a suspected sighting, while all other funds are expended on Guam and are targeted at preventing snake arrival at defined points of entry. Previous research (Burnett et al. 2006) indicates that this may actually focus too much on the points of entry if snakes have already evaded detection there. Our results concur.

We calculate the spatial-temporal treatment schedule that minimizes the overall net damages and costs in present value terms for a thirty year period.

We find a present value of expected damages of $371 million accumulated over 30 years from an initial invasion of a single snake at one of three possible entry locations with no EDRR action. We start the optimization with treatments indicated for all cells when and where the current year damages exceed the current year costs, treatment of which will certainly reduce the social welfare losses. We then test whether treating these cells or neighboring cells before the damages exceed the current year costs reduces the present value of net damages by reducing the future populations and their damages. We find that under our parameters for the discount rate, growth, costs and damages, it does not.

We find that treatment reduces social welfare losses to $101 million dollars. Over the thirty year period, we find the need to treat just over 3000 cells, or 8% of the island. The treatment plan also delays any search until the 12th year after an invasion. This result is driven by the interplay between the discount rate and the growth function; the chances of finding snakes when they are spreading out across the potential habitat and are at low densities, and causing low damages, mean that waiting discounts the costs more than the growth in the damages.

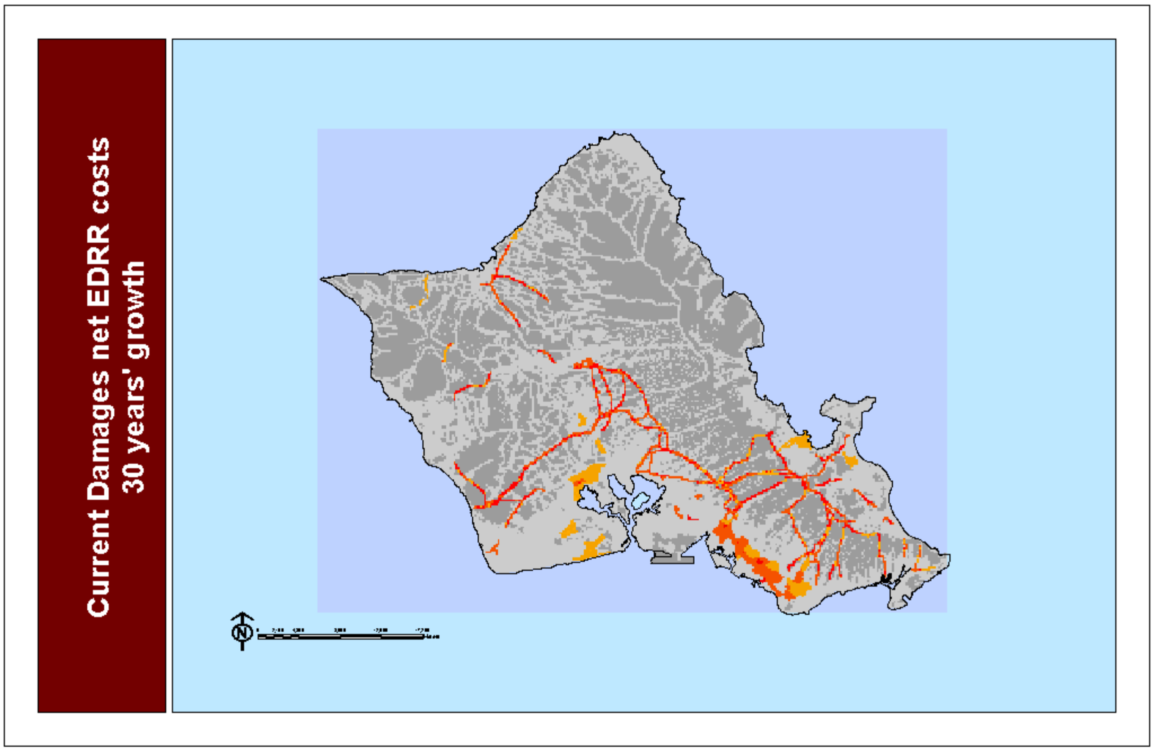
The hazard rate (the probability of arrival during the intervals between arrivals) should affect these results in two ways. We have used a thirty year time frame in part because this is the time, given the growth parameters, that it should take for the entire island to have snake populations. In this time frame, damages have just grown to exceed the present value of costs for an entire-island sweep (which occurs in year 28, see section 3), which suggests that is the appropriate time to switch from an EDRR policy to a control policy, where removal of the snake population is undertaken directly.

Figure 4 shows a snapshot of the net current damages (i.e. only the damages in that year) that would occur if all cells were treated in the last year of invasion. In a significant majority of cells, the current damages are below the current EDRR costs (shown in grayscale), and intervention cannot be justified on the basis of current damages alone. The area for which damages do exceed costs (shown increasingly from orange to red), so that EDRR treatment is cost-effective

[8] Mitochondrial DNA evidence suggests that the entire population of snakes on Guam may have originated from a single female.

in this single period, are obviously also the areas where optimal EDRR should be targeted. One can see that these cells integrate damages, costs, and the biological spread in such a way that EDRR treatment, when there is only funding for sporadic and incomplete treatment, should focus on not just the areas closest to the most likely point of entry (HNL airport) but also along roadways with major power lines adjacent and in locations where human-snake interactions would be high (the orange areas along the southeastern coast in Figure 4 are the densely populated Honolulu and Waikiki areas).[9]

Figure 4: Current net damages across first 30 years of invasion



If opportunities for effective EDRR are missed, the snake population will need to be managed as an existing invader, where the marginal costs of the population of an area are weighed against the marginal benefits. We examine the current case of Miconia calvescens to illustrate the different policy implications.

2.3 Miconia calvescens

One well known significant threat to Hawaii's forest ecosystems comes in the form of the woody shrub, *Miconia calvescens*. A member of the Melastomataceae family from Central America, the plant was purposefully introduced to Hawaii. Starting in a handful of back yards and arboretums four decades ago, it has been spreading with increasing rapidity on the islands of Maui and Hawaii. It is also present on Kauai and Oahu, though it has not yet claimed significant acreage in either location. Miconia is not thought to be present on the island of Molokai. The length of

[9] In spite of the level of urbanization, scientists assure us there is plenty of prey available, and as the snake is nocturnal and reclusive snake, it is likely to do well in an urban environment with many places to hide.

time from the initial invasion and the considerable efforts that have been expended in controlling and surveilling for the tree's expansion over the last two decades mean that there is sufficient data to generate estimates of growth and control costs. Extracting this data from the resource managers and processing it into a useable form is a challenge we discuss at greater length in section 3.

When considering optimal management of Miconia, two spatial considerations matter. First, the likelihood and magnitude of the invasion (as measured by population growth over time) will vary spatially according to the current population and dynamics of growth. Second, the natural capital assets may be unevenly distributed across space.

We use Geographical Information Systems (GIS) to map the current and future populations of miconia on the island of Oahu, Hawaii, and the potential damages to water quantity, water quality, endangered bird habitat, and native habitat housing endangered plants, snails, and insects. We develop a control cost function that includes locating and treating miconia plants. Using optimal control theory, we find the spatially dependent optimal population levels of miconia and the paths to these populations over time.

We define our problem so that we minimize the expected costs and damages from the presence of and control activities undertaken against the invading species. In an advance over the current literature, we allow costs and damages to vary spatially as well as temporally. Thus the objective function is:

$$\underset{x_{it}}{Max} \int_0^\infty -e^{-rt} \sum_i \left(\int_0^x c(n_{it}) d\gamma + D(n_{it}) \right) dt \tag{9}$$

subject to:

$$\dot{n}_i = g(n_i, n) - x_i \tag{10}$$

$$0 \le x_{it} \le n_{it} \tag{11}$$

$$n_0 = n(0)\,, \tag{12}$$

where *i* denotes the spatial location (grid cell), *t* represents the time period, n_{it} and $\dot{n}_{it}$ are the population of the invasive species in a given location and its associated time derivative, n_t is the total population at *t*, $g(n_{it}, n_t)$ the growth function of the invasive, x_{it} represents the number of removals, $c(n_{it})$ the marginal cost function for removals, which varies with population level, and $D(n_{it})$ the damages incurred at population n_{it}. In the following, we drop the time subscripts for ease of notation.

Defining the current value Hamiltonian for each location as:

$$H_i = -\int_0^{x_i} c(n_i)d\gamma - D(n_i) + \lambda_i[g(n,n_i) - x_i]\,. \tag{13}$$

Applying the Maximum principle and rearranging the subsequent first order conditions, we find

$$D'(n_i) = rc(n_i) - c(n_i)g'(n,n_i) - c'(n_i)g(n,n_i) \tag{14}$$

In this way, we see that at an optimal population, the marginal damages should be equated with the costs of maintaining that population for the location. Were marginal damages to be higher (lower), additional (fewer) trees could be removed, reducing the overall losses. Areas with higher marginal damages, then, will have more trees removed.

We divide Oahu into 16 ha plots, or cells, to analyze the optimal management of miconia for the island over space and time. Each cell contains information on habitat quality and the current presence of the invading plant. We assume that the current invasion has already been underway for 37 years, and was initiated by purposeful individual plantings.

2.3.1 Miconia Growth

Invasive species managers on the heavily invaded island of Hawaii estimate that the densest areas contain approximately 100 trees per acre. Our spatial cells are 16 hectares each. Carrying capacity per cell is thus 3,952 trees.

For population, we use the same functional form expressed for brown treesnake in equations (6) and (7). In the case of the tree, however, the transition between the exponential growth and spread and internal logistic growth occurs at 20 trees in a cell with a maximum snake carrying capacity in any cell (*K*) of 3,952 trees. Further details are available in Burnett et al. 2007.

2.3.2 Miconia Damages

We estimate damages from Miconia as evolving from indirect ecosystem services as well as non-market goods like biodiversity. Particularly significant threats are a reduction in habitat for endangered species and a shift in the hydrological cycle that may reduce freshwater recharge and increase runoff and sedimentation. Details of the damage estimates are available in Burnett et al. 2007. In short, marginal damages for any given location will be calculated according to:

$$d_{it} = d_{bird\ habitat\ or\ range} + d_{water} + d_{native\ habitat}\,. \tag{15}$$

Because not all locations will have all of these characteristics and because water damages will vary by aquifer, marginal damages will vary spatially. We find that in our analysis marginal damages range from \$0.22 per tree to \$19.06 per tree. Marginal damages from bird habitat losses range from \$0.00 to \$6.34 per tree; damages from watershed losses range from \$0.22 to \$0.70 per tree; damages from native habitat losses range from \$0.00 to \$12.02 per tree.

2.3.3 Control Costs

The marginal cost of searching and treating *x* trees is:

$$c(n_i) = \left(\frac{\$39{,}520}{n_i^{1.6258}} + 13.39 \right) \tag{16}$$

There are two separate activities that must occur – the trees must first be found, then treated, so that the cost function consists of two parts, the "search" component and the "treatment" component. While the unit cost of treating a tree with herbicide and/or cutting a tree may be constant across population levels, the cost of finding a tree is rapidly decreasing in population size.

We determine the two components for Oahu in the following manner. The search component involves a fixed cost which depends on the island's potential habitat acreage and which decreases with increased access to that habitat. Based on discussions with resource managers, searching one average acre for Miconia costs approximately \$1,000. The numerator of the search component for each spatial cell on Oahu is \$1,000 per potential acres, or \$39,520 per 16 ha cell.

The ability to search an island's habitat will also depend on several characteristics of the surrounding area, such as density of vegetation, the steepness of the terrain, etc. One major determinant is ease of access into the potential habitat. We use the combined length of roads and trails as a proxy for this variable. The length of roads and trails as compared to Molokai, the most expensive island to search because it has the fewest roads and trails per acre of habitat, is used to determine the exponent on population in the denominator of the search component. Higher values imply greater ease of access, which translate into lower search costs. Due to the number of well maintained roads and trails throughout Oahu's forests, Oahu has the highest search coefficient of all islands, at 1.6258. Additional details on the specification of the cost function are in Burnett et al. 2007.

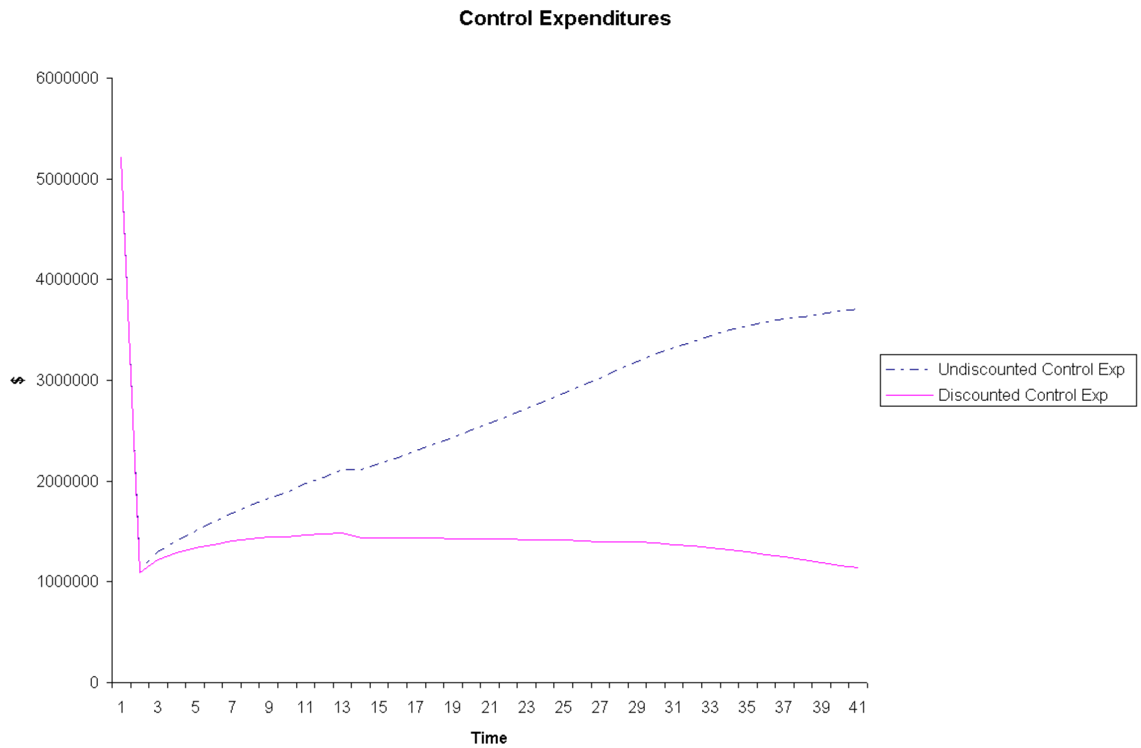
2.2.4 Miconia Results

If left untreated, the damages from miconia will grow at an increasing rate into the foreseeable future. Unchecked damages over the next 40 years have a present value of approximately \$627 million dollars using a 3% discount rate.[10] This is the cost of doing nothing.

[10] Under our parameterization of the spread, it will take approximately 80 more years for miconia to blanket its potential habitat on Oahu in the way that it now covers Tahiti. In part because planning horizons are short and in part because new treatment technologies are likely to evolve in the long run that will change control costs, we focus on the more immediate future and investigate the benefits of management over a forty year time horizon. In particular, remote sensing technology already can identify large stands of Miconia, and improvement in this technology may allow for quick identification of smaller Miconia populations. Additionally, since the loss of an endangered species is irreversible and the demand for groundwater is likely to change over time as well, damages may not be constant over the long run either.

Using the parameterization described above, we solve for the optimal populations in each spatial location over time. We find that 9616 ha need immediate treatment at an expected cost of $5.21 million dollars. This should be followed by spending that keeps the population in each location cell somewhere between 43 and 705 trees per 16 ha plot. Over 40 years, this cost will increase from $1.12 million per year to $3.71 million per year. The total present value of control costs from now until 40 years into the future should be $54.5 million, using a 3% discount rate.

Figure 5: Miconia control costs over time



As shown in Figure 5, the initial large immediate outlay of $5.21 million should be followed by continuous control expenditures. Note that while these expenditures are increasing in current dollars, after year 12 they are decreasing in present value. We therefore emphasize that long run planning is essential to optimal management; it will become increasingly difficult to find new funds for management, so that setting aside funds for future management so that they can keep pace with the discount rate will be helpful to achieving optimal management goals.

Figure 6: Optimal control vs. no control over time

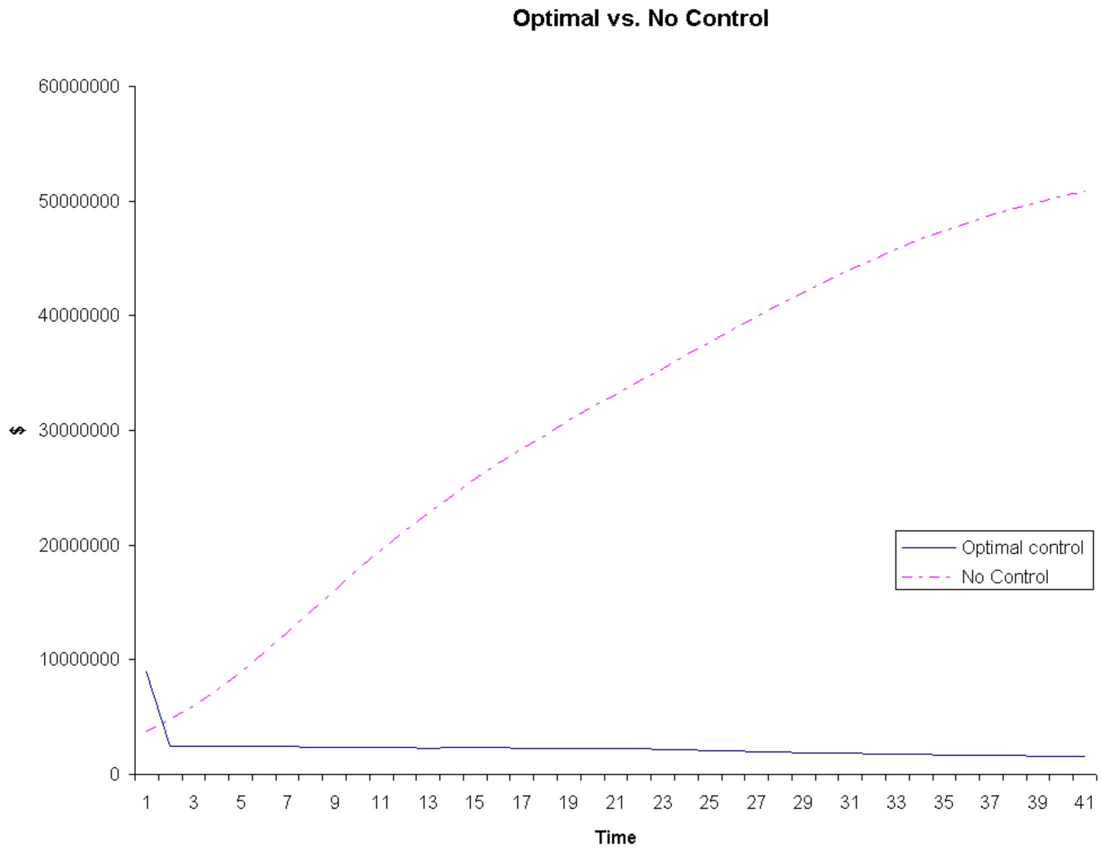


Figure 6 shows the comparison outcomes of no control, as measured by damages, to those of optimal control, as measured by damages from untreated trees plus the control costs for treated trees. We find that the returns to control grow in present value over time. In the first year of management, current expenditures and damages ($9.0 m) are more than current untreated damages ($3.8 m) by $5.2 million. By the second year, however, optimal management costs $2.2 million less than untreated outcomes and the benefit: cost ratio increases to just over 10:1 by year 40, with annual present value net benefits between $14 m - $17 m beginning in year 12. Net benefits over the forty year period from optimal control are $534 million.

3. Discussion

3.1 Parameter choices

3.1.1 Grid cell size

Grid cell size matters in determining optimal policy for several reasons. Foremost, because the cost of search exhibits economies of scale that are spatially dependent, the finer the gradation is, the flatter the marginal costs as a function of population will be. Flatter marginal costs tend to increase the optimal population level. In the case of miconia, we see that including finer gradation in the analysis significantly increases the population of trees. When we analyze the entire Hawaiian islands as one continuous habitat, the optimal population of trees is 31,295 (Burnett et al. 2006). When we subdivide the analysis by island, we see that the optimal population of trees for Oahu is 5495 and the optimal population for the state is 63,504 (Kaiser et al., 2007). Finally, when we subdivide Oahu into 16 ha plots, the optimal population for the island will eventually reach almost 1 million trees and seedlings (52 years from the present), though the population in each 16 ha plot will range from only 40 to 705 trees and seedlings. (Burnett et al., 2007).

Additional considerations include the availability of reliable GIS data at finer resolutions and the computational limitations of perhaps millions of choices across cells, even if the choices are binary. In the case of miconia, habitat cells could not be reliably determined at any smaller resolution. In addition, there was little benefit from smaller units of analysis because helicopter searches can cover several acres in one pass. In the case of the snake, search is time-consuming and only small areas can be searched in any one night. Since the island of Oahu is considered all potential snake habitat, the resolution did not affect this parameter. Finally, since treatment was a binary decision to search or not search, having over 1 million cells, though cumbersome, was not impossible with the application of constraints from theory. In the miconia case, while theory guides the population levels in the cells, the populations are continuous and the reduction in cell numbers dramatically increases the ability to solve the problem.

3.1.2 Growth

Both the internal growth parameters, here 0.3 for miconia and 0.6 for snakes, and the diffusion rates, here 0.208 km2 for miconia and 1.067 km2 for Brown treesnakes, are important factors in determining optimal policy. Combined with marginal damages, faster growth will increase the need for immediate treatment and increase the probability that delaying efforts will result in having to choose accommodation of the invasion over eradication or control at a small population. Faster growth will also lower marginal costs of treatment more quickly so that delay again is less beneficial.

Not only is delay more costly, inadequate control efforts are more wasteful. If control is applied at levels where growth continues to expand within a cell, the benefit of that control effort is lost to future damages. The faster the growth rate, the greater the penalty will be.

3.1.3. Costs

For most invasive species, detecting the species is a significant portion of costs, at least at low densities. The area for which search costs are defined, then, will affect the marginal costs as a function of population and the optimal population, as described above. When costs are determined spatially, however, this concern is alleviated. If the species is known to be present in an area, like miconia is, then it is inappropriate to apply costs spatially since it does not allow the optimal population to vary within the area. Optimal population may indeed vary as a function of damages, growth, and costs. If there is no known population, however, and if the optimal population were its presence detected was low or zero, as it is in the case of the brown treesnake (Burnett et al. 2006, Burnett 2007), then costs can be applied spatially. EDRR is a valuable and distinct management tool that needs greater analytical attention.

3.1.4 Damages

Though damages for ecological benefits are often very uncertain, in all of our cases we have at least one market good to which we can tie damages, providing lower bound estimates. Thus we need not fear that our damage estimates are too high and that accommodation of these invasive species is actually the optimal policy. We may need to be concerned with upper bounds, however. If damages are significantly underestimated, it may be that eradication is the optimal policy in spite of high search costs or the inability to prevent future entries. This inability to prevent future entries, however, requires prevention and possibly EDRR activities be considered in this optimal policy decision.

EDRR is again an appropriate policy for considering the range of damages that might matter. Under our parameterization, we find that spending on EDRR for the snake should occur when the present expected damages exceed the present costs. Thus if one fears that an endangered species is undervalued, for example, then cells in which the species is present may deserve more EDRR effort. The essential finding that management activities must simultaneously incorporate expected costs, damages, and growth does not change.

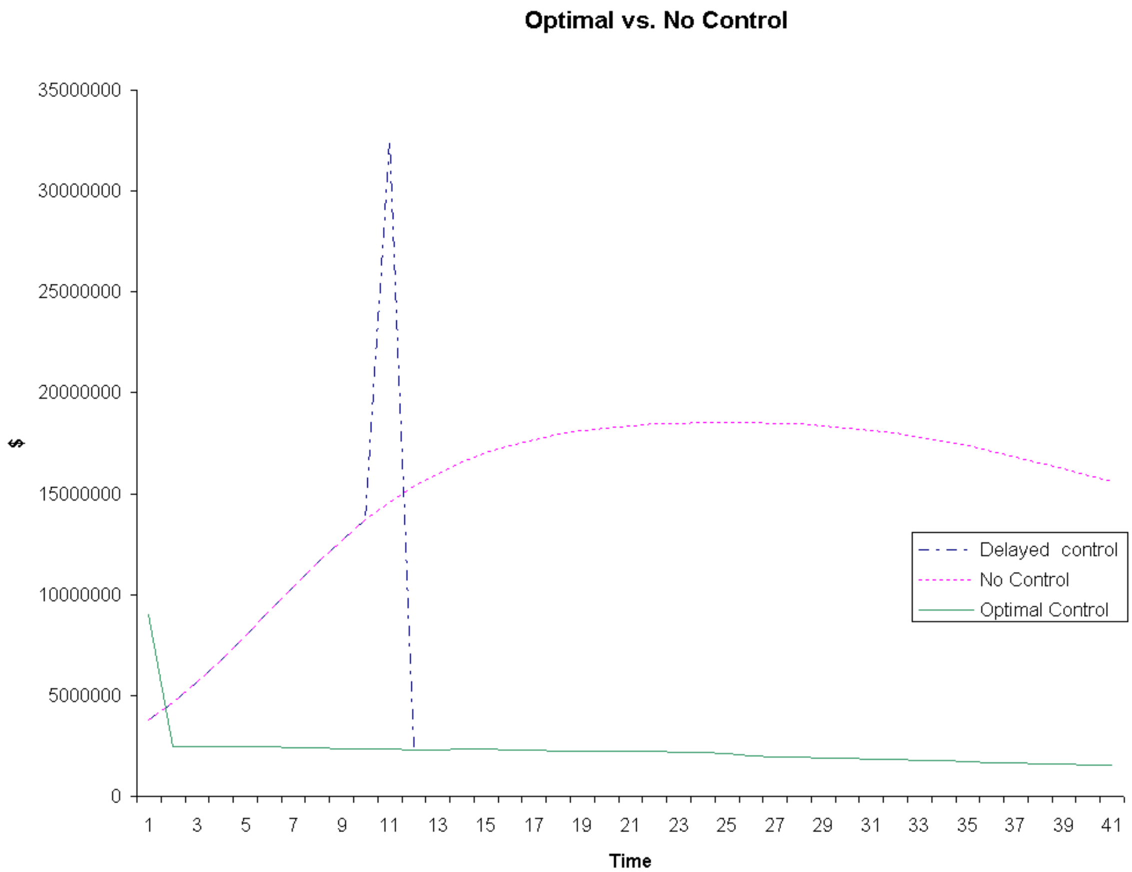
3.2 Temporal Application of Policy

3.2.1. Delays in Policy Initiation

The annual expenditures that maintain the optimal populations of miconia are, as figure 5 shows, around one to 1.5 million dollars. (Note that a steady state population is not reached in 40 years because the population of trees has not reached all habitat in that time.) Delaying the start of treatment will increase the need for current outlays when treatment does begin, as more trees will need to be removed. Figure 7 illustrates. In spite of the large returns that can be gained from delayed control, it is evident from figure three that there may well be a point at which it is too late, and accommodation should be favored over expensive removals and permanent control because the present value of uncontrolled net damages will be lower than that of controlled damages and costs.

The specific time at which this switch would occur, however, is a decreasing function of the discount rate and an increasing function the time horizon under consideration. An infinite time horizon is preferable to our current short term analysis, especially given the irreversible nature of many of the ecosystem benefits, and we do not seek to calculate this. In the case presented here, though net benefits of control fall from $534 m to $448 million, a loss of $86 million over just ten years, it is still worthwhile to initiate delayed control.

Figure 7: Cost of Delayed Control



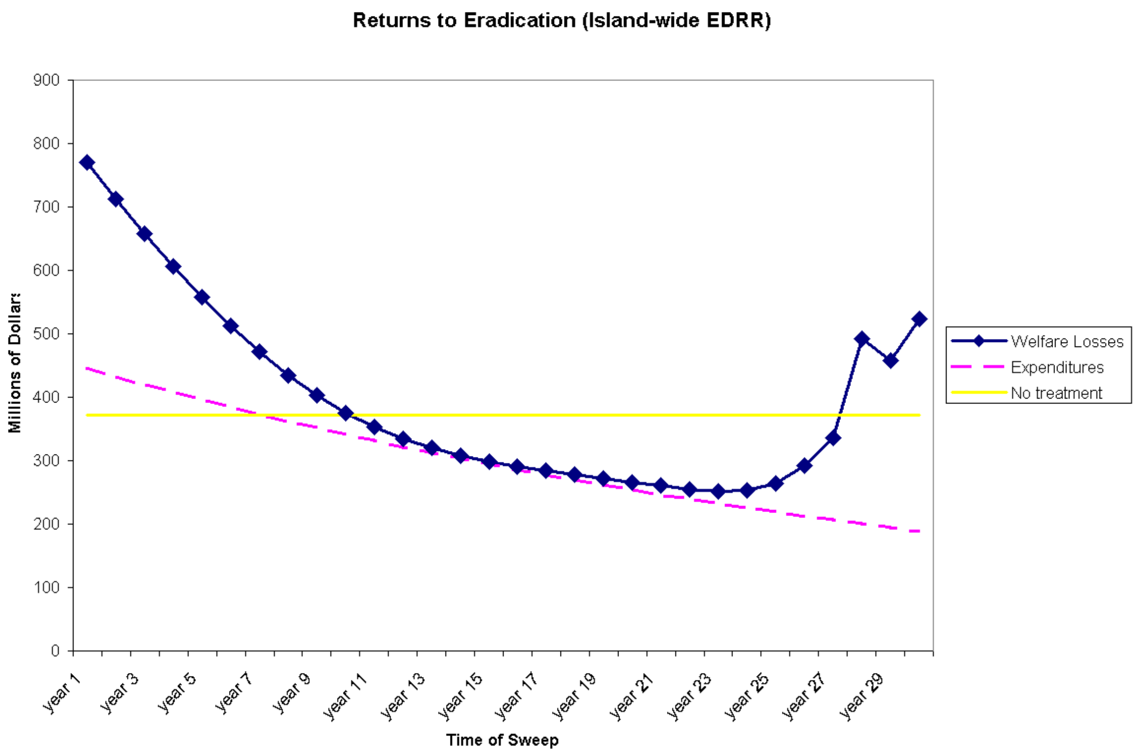
In the case of the snake, though delaying initial search until the 12th year after an invasion appears optimal, two caveats are offered that suggest additional benefits to earlier search. First, in an island-wide sweep, scientists may become confident that an early eradication is complete at a lower total cost than $447 million as they gain evidence from the search experience. Second, our damage function is not currently applicable to extension beyond thirty years because of the expected irreversible loss of the elepaio bird species. The 11 bird species extirpated on Guam were lost in fewer than 40 years, and a similar time frame for Hawaii can be expected. Thus if eradication efforts are deferred, the irreversible loss of the species imposes a dramatic threshold damage penalty and reduces the expected benefits of further action, which will then only serve to reduce human-snake interactions and electrical supply damages.

3.2.2 Application of inappropriate policy for the level of invasion

Eradication is almost always a stated goal for agencies charged with managing invasive species. The snake may be a case where eradication or at least low populations are optimal (Burnett et al. 2006, Burnett 2007). Under our specifications, a full island search would rid the island until the next arrival, therefore there may be some benefit, though not economically optimal, to periodic island-wide sweeps. We investigate the returns to island-wide sweeps at various stages to highlight these tradeoffs. The cost of a complete island search is estimated at just under $447 million. In the worst case scenario, if an island-wide search is conducted, and then another snake enters in the following year with no follow-up treatments, the total social welfare losses are $771 million, far more than never conducting the search.

However, if a single island-wide search is conducted between years 11 and 27, the net benefits of the search are positive, even with re-infestation the next year. Social savings range from $18 million to a peak of $120 million before they begin to fall again and become negative after year 27. This is due to the fact that the damages grow exponentially with the expansion of the snake, so that while the present value of the costs is constantly falling, the damages from the spread of the snake outpace the discounting of the future damages. Waiting until year 30, for example, will have total social losses of $523 million. Thus, the use of a lower discount rate might actually deter EDRR activities because the costs will appear higher for a longer period; using a 3% discount rate, the damages do not start to grow rather than decrease until year 16. [11] Figure 8 illustrates.

Figure 8: Returns to Eradication (Island-wide EDRR)



Extensive but random search, however, is likely to raise costs more than reduce damages, unless it is comprehensive (island-wide) and occurs between the 11th and 27th year of a successful invasion. Note then that early, incomplete search may work against long run efforts at snake prevention and control, since repeated failure to produce a snake may significantly reduce the public perception of the magnitude of the problem and their willingness to devote resources to it. When search is random but incomplete, the present value of social costs regularly lies between $450 and $750 million. Successful damage-minimizing EDRR activities target areas that have

[11] At year 15, even with exponential growth, no cell has more than 28 snakes, just over 10% of carrying capacity. This begins to change rapidly in years 15 to 30.

high expected net damages, either because they have a combination of high expected populations, high asset values, and low search costs. Small changes in treatment allocations that explicitly weigh expected damages, population growth, and treatment costs can dramatically improve random solutions. Thus, random or incomplete efforts may not be better than doing nothing, but strategic action can dramatically improve outcomes.

3.2.3 Changes in optimal policy when funds are uncertain

In the case of a potential invader like the brown treesnake, we determined that the optimal policy for EDRR is not to search until populations are high enough that there is a chance to find them at a reasonable cost, here in the 12th year of an invasion.

A likely restriction for managers, however, is the inability to plan for EDRR funds over a long period of time. We investigate what the optimal policy should be if funding can only be secured in 5 year increments. In this case, we find that at the end of the first 5 years, if there is uncertainty regarding future funding, one is best off treating a small number of cells with high net expected damages, reducing the overall expected cost by about $150 m to $227m. Treating a slightly larger group of high expected damage cells after another five years reduces damages to $142 m, while additional treatments at years 15 and 20 reduce the damages to $126 m. Compared to the periodic island-wide sweeps, this targeted EDRR activity is preferable, in spite of the fact there may still be snakes present. Furthermore, it suggests that taking decisive and targeted EDRR action, even though it may not be the optimal action, is more likely to reduce overall damages than to increase expenditures, especially when those expenditures are large.

4. Conclusions

Optimal management of invasive species will minimize total losses from invasion, including ecological damages, economic damages, and the costs of managing these invasions. The primary instruments for managing invasive species are prevention, early detection/rapid response, and control. Efficient management programs will vary across time and landscapes. In this paper we explore efficient spatial and intertemporal management for three invasive species in Hawaii, the coqui frog, miconia, and the brown treesnake.

We begin by considering economic damages from the coqui frog. We find that the presence of the frogs has a significant negative impact on property values. For properties within 500 meters of an official coqui complaint, property values decline 0.16%. While we do not explicitly model efficient management of the frog in this work, we produce an estimate of net marginal damages from the spatial spread of the frog as a function of the properties in an invaded location. In future work, this estimate will be used in conjunction with spread and capture cost estimates to generate optimal management policies for the frog.

For miconia, we find that optimal control entails treating immediately treating approximately 9,616 hectares on the island of Oahu, at an expected cost of $5.21 million. This should be followed by spending that keeps the population in each location cell between 43 and 705 trees per 16 ha plot, depending on the spatial location of each plot, across an eventual total of about 53,000 ha.

In the case of the potential invader, the brown treesnake, we find that the optimal management program entails EDRR on less than 10% of the island of Oahu over a thirty year period. While the cost of inaction is approximately $371 million, optimal treatment reduces social welfare losses to $101 million dollars. This analysis confirms that search and removal should be focused not only on likely areas of entry, but around potentially high damage areas as well. We further find that after approximately 30 years, the benefits of EDRR should begin to be supplemented by direct control.

We conclude by investigating the sensitivity of policy decisions to key model components. We find that results are sensitive to grid cell size, as this affects the steepness of the marginal cost function and the resolution at which other parameters can be applied. Rate of growth will also influence the optimal program. Faster growth will increase the need for immediate treatment and will lower marginal costs of treatment more quickly. Specification of growth will also be related to the adequacy of management levels. Inadequate control efforts are found to be wasteful. If control is applied at levels where growth continues to expand within a cell, the benefit of that control effort is lost to future damages. The faster the growth rate, the greater these losses will be.

Deliberation consideration of space in the model improved our understanding and ability to model costs of control and damages from miconia and the brown treesnake. Temporal insights were advanced from previous work as well. For miconia, despite the large returns that can be gained from delayed control, we find a point at which it is too late, and accommodation should be favored over expensive removals and permanent control. For the brown treesnake, it appears that delaying initial search until the 12th year after an invasion is preferred to initiating search immediately.

Current policy regimes often tout eradication as the most favorable management option. Under our parameterization, we are not able to find any case in which full eradication and maintenance of a zero population is optimal. We also find that random or incomplete efforts may not be better than doing nothing, although strategic, efficient action can obviously improve outcomes.

Finally, because the dedication of future funding to invasive species efforts is often unknown or extremely limited, we investigate optimal brown treesnake policy under funding that can only be secured in 5 year increments. In this case, we find that treating cells with the highest expected damage first will reduce total losses by the most. This is an important result for policymakers in Hawaii and the Pacific, as limited brown treesnake funds are currently focused on searching around likely points of entry, rather than around high-valued assets at risk.

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Economic Evaluation of Policies to Manage Aquatic Invasive Species

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1. Introduction

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). The main 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).

Approximately 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 regulations for ballast water nor biofouling. Time and fuel considerations by shippers on the north-south route 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 U.S. and Canadian policy to prevent the spread of marine invasive species in the Pacific coast of North America is inadequate.

New policies are needed to promote biosafety and address invasive species along coastlines on a multinational scale. In 2004 the International Maritime Organization (IMO) formulated a numerical limit guideline for ballast water emissions (IMO, 2004). Biofouling emissions did not receive the same attention. Ultimately, the control effort will depend on the actions taken by shippers that in turn depend on economic incentives. The paper seeks to analyze the potential for reducing the threat of invasive species under a few policy options.

There is a paucity of economic analysis of policies to regulate the biological pollution problem of invasive species. Lovell et al. (2006) provides a helpful review of the economic literature as it applies to invasive species (aquatic and otherwise) that deal with various aspects other than specifically policy options for solving the problem. When there are some estimates of damages due to invasive species, there have been some quantitative analyses assessing incentives and strategies to solve the biological pollution problem [(Fernandez, 2006), (Fernandez, 2007)]. However, those analyses have focused on amount of abatement needed and ways in which multiple locations can coordinate efforts rather than explicitly reviewing policy options to spark abatement. Preventative policy measures exist but there has not been an economic analysis of their general cost effectiveness and the incentives for shippers and ports.

The present paper should be viewed as the case of a discussion of the framework for policies that require more damage estimates through careful economic valuation techniques in order to quantitatively work out the details. Hence, the following paragraphs will outline with analytic simplicity some basis for exploring policies that can benefit from efforts to quantify damages and benefit for avoiding invasive species in the marine environment in order to formally measure all of the positive aspects of the policies discussed.

Biologists assert prevention is necessary to abate invasive species due to risk and uncertainty of locating exact emissions per ship from both vectors (ballast water and biofouling) uniformly across time and space and ineffective eradication (Ruiz and Carlton, 2003). Social benefits of preventative measures that are unobservable with positive externalities lead to suboptimal levels of private investment. There's a reason to investigate the feasibility of public policy intervention to promote prevention.

The dependence of one port's security on the behavior of others may partially or in some cases almost completely negate the payoffs it receives from its own investment in protective measures. This case of conditional dependence of protection should be addressed in any efforts to regulate invasive species possibly traveling between connected ports. The decision to invest in monitoring or controls necessarily means balancing the cost of doing so with the reduction in the risk of an invasion from a ship not only from those ships entering their port first from outside of a country's Exclusive Economic Zone (EEZ), but also from within the EEZ, as mentioned previously of the North-South traffic as well as the East West traffic along the Pacific coast of North America. The incentive by one port to invest is greatly decreased if other ports fail to adopt protective measures, thereby leading to greater threats overall. The decision for no protection may be a Nash equilibrium even though there are net benefits to everyone from protection. However, unlike a Prisoner's Dilemma, there may be a Nash equilibrium where some agents want protection. The role for public sector intervention to overcome the decreasing incentive for investing in prevention if more ports do not coordinate should consider coordinating mechanisms to induce some protection and reduce the need for what appears to be futile eradication efforts.

How can one port insure that enough ports will invest in prevention so that others follow to avoid invasive species altogether? That question is addressed in the first part of the paper that deals with policies between ports. Then, the other realm is to deal with the interaction between the port and ships. That context is dealt with in the second part of the paper.

The analysis involves a model of interdependence of ports for the invasive species problem with a negative externality that creates a disincentive to invest in prevention. The policy goal is then to internalize the externality.

1 A. Port Model

A basic picture is a one period model of N risk neutral seaports designated by S_i, i = 1...N . The seaports represent the public resource managers deciding on protection. The choice can be seen as discrete: invest or not. Alien invasive species population is A_i, i = 1...N for various ports. The risk of loss is: D A_i. It is possible to further define A_i as a function of how much abatement is applied as will be described below in terms of M . The probability of a loss arising on seaport if it has not invested is p so expected loss is pD A_i. If the seaport has invested in prevention, risk=0. Assume for really simplistic math to motivate the discussion that ports are symmetric and identical. An additional risk from another port that did not inspect or stop a ship from spreading invasive species beyond its port is x.

On any given ship trip there is a probability p that a seaport without a preventative plan accepts a ship with invasive species that invades its own port. The probability x refers to a ship from another port arriving to invade a second port. If there are N ports greater or equal to 2 seaports the probability per trip that this ship will be transferred from seaport i to j is x/(N-1). The probability per trip that a ship at a port without a prevention system will invade is probability p + x. Assume that D A_i from one invasion is as harmful as from multiple invasions, so D A_i is not additive. As probability is low and the D A_i may be catastrophic, a single occurrence is all most consider for making the decision about protection at the port.

The seaport has perfect information on risk and costs of protection and has to make a choice between investing in protection M or not. Think of M as monitoring a discharge permit or some other form of inspection. The following table has payoffs for 2 ports (S_1, S_2) where R is the revenue for a port.

	M	No M
M	R-C, R-C	R-C-xD A_i , R-pD A_i
No M	R-pD A_i , R-C-xD A_i	R-[pD A_i +(1-p)xD A_i], R-[pD A_i +(1-p)xD A_i]

The cost per ship of investing in monitoring protection is C. The payoffs if both seaports invest is R-C for each. And, the rest of the table is straightforward.

It is imperative to ask what conditions will lead seaports to invest in protective monitoring? For monitoring to be a dominant strategy R-C > R-pD A_i and R-C-xD A_i > R-pD A_i - (1-p)xD A_i . The first inequality indicates C < pD A_i where the cost of protection is less than expected loss. This can be a condition for an isolated seaport. The second inequality from above reduces to C < pD A_i -pxD A_i =pD A_i (1-x). This is definitely a tighter inequality reflecting the possibility of influence from a second seaport. This influence reduces incentive to invest in monitoring. In isolation there is complete freedom from risk by investing in protective monitoring.

With interdependencies between ports, there is no such guarantee. Even if a few invest there remains a risk of loss due to the other ports having influence. Investing in protection buys little assurance when there is the possibility of influence from others.

In a 2 agent problem with identical costs, one can determine optimal behavior of each seaport without communication. In this noncooperative environment if C < pD A_i (1-x), then both seaports will want to invest in protective measures (M,M); if C >pD A_i then neither agent will want to invest in protection (N,N). If pD A_i (1-x) < C < pD A_i then there are two Nash equilibria and the solution is undetermined.

If seaports have different costs of investing in protection measures, then there may be a Nash equilibrium when one seaport invests and the other does not. Specifically, let C_1 and C_2 be the costs of the two seaports, then (N,M) will be the Nash equilibrium if $C_1 >$ pD A_i and $C_2 <$ pD A_i (1-x). This mixed equilibrium requires that the two costs differ by at least pxD A_i.

A general case of N identical seaports all symmetrically placed means if all but 1 of the seaports have invested in protection, then risk facing the remaining one is identical to what would be in isolation; there is no risk of influence from others. At the other extreme, suppose non of the other N-1 seaports have invested in protection; then if the remaining agent is protected it still faces risk originating at N-1 other locations.

If three ports are the focus of S_i, i=1,2,3, then define E(3,0) as the expected negative externality to any seaport i that has protection if the rest of the three seaports have no such protection. E(3,0) is given by (x/2)[1-x/2)]D A_i. When one other seaport has installed protection then the expected negative externality is given by (x/2)D A_i since there is only one seaport without protection and it transfers a questionable ship to the first seaport with probability x/2. If there are four seaports then the expected negative externality is as follows, based on how many adopt protection: E(4,2) = (x/3)D A_i; E(4,1)=(x/3)[1+(1-x/3)]D A_i; E(4,0)=(x/3)[1+(1-x/3)+(1-x/3)²]D A_i.

For N>1 seaports, this can be generalized as

(1.1) E (N,0) = [x(n-1) $\sum_{t=0}^{n-2}[1-x/(n-1)]^t DA_i = [1-[1-x/(n-1)]]^{n-1}]DA_i$

The limit on this expression as n approaches infinity is:

$$\lim_{n\to\infty} E(n,0) = (1-e^{-x})DA_i.$$

When there are n seaports the payoff to seaport i from not investing when n-1 do not invest is

(1.2) R-pD A_i -(1-p)E(n,0).

The payoff to port i from investing is

(1.3) R-C-E(n,0).

Comparing (1.2) and (1.3), investing is the better strategy if and only if

(1.4) C < p[D A_i -E(n,0)] .

Equation (1.4) implies that there is less incentive to invest in protection with higher negative externalities associated with seaport interdependence. What is the structure of a set of possible Nash equilibria? For the two port case (M,M) is the dominant strategy if C <pD(1-x) and a Nash equilibrium if C<pD A_i . The strategy (N,N) is a dominant strategy if C > pD A_i and a Nash equilibrium if C > pD A_i (1-x).

There is an interval pD A_i (1-x) < C <pD A_i in which both (M,M) and (N,N) are Nash equilibria. For the N port case, (M,…,M) is the dominant strategy if C< p[D A_i -E(n,0)] and [N,…,N] is the dominant strategy if C > pD A_i . When C is between 2 values, there are 2 equilibria.

1 B. Policies Between Ports

Insurance discourages investment in protection if insurers face moral hazard problems due to their inability to detect careless behavior on the part of the insured ports who know that they will receive compensation should they suffer a loss. In this case, one can lose a (M,…,M) equilibrium if the ports are allowed to insure themselves against losses. If moral hazard problems can be eliminated through the terms of the insurance contract (deductibles, coinsurance) and/or monitoring and inspection, then insurance with actuarily fair premiums encourage a risk averse port operating in violation to adopt protection whenever the cost of the measure is less than the reduction in expected losses.

It is necessary to deal with the externalities created by other ports who do not invest in protection and due to interdependencies cause damage to other ports. Suppose that an invasion happens in port 2 due to lack of investment by port 1, and port 1's insurer is required to pay for the damage to port 2. This is not how current insurance practice operates. An insurer who provides protection to S_i is responsible for losses incurred by port i no matter who caused the damage. If the damage from insured risk is due to negligence or intentional behavior there are normally clauses in the insurance policy that indicate that losses are not covered (such as with arson). One reason for this contractual arrangement between insurer and insured is the difficulty in assigning causality for a particular invasion. A single insurance program that provided coverage to all ports would, however, want to internalize the externality.

It may help to illustrate this point with the interdependent port case with 2 identical seaports (S_1, S_2) where each port has its own insurer who charged a premium based on expected losses. If S_1 contacts its insurer inquiring about a premium reduction for undertaking a protective measure, knowing that C<pD A_i. If the insurer knows or suspects that S_2 has not invested in protection, it will only be willing to reduce the premium by p(1-x)C because of the interdependent effects from S_2 to S_1. On the other hand, a single insurer covering both ports that commands the market (monopolist) or represents a social insurance program can require both S_1 and S_2 to invest in the protective measure and in return give each port a premium reduction of pD A_i.

The real world example of insurance related to marine invasive species pollution involves New Zealand. All costs associated with inspection, cleaning and abatement are the responsibility of the importer in a program run by the New Zealand government.

If a port that caused damage to other ports by not adopting a protective measure were held liable for these losses, then the legal system would internalize externalities due to interdependencies. For the two port example, suppose that S_1 knew that by not investing in protection it would be liable for damage that it caused to S_2. It would invest in protection whenever C < (p+x)D A_i. Although the liability approach has attractive theoretical properties, it faces practical problems due to high transactions costs related to determining causes of loss. The discussion presented in the context of ports and shippers below combines liability with other policies based on the limitation of liability alone. And, the framework for suggesting liability below is through the formal program, International Ship and Port Facility Security (ISPS) Code that already exists.

Because of the difficulty of attributing damage ex post to a shipper through liability involving legal proceedings, Segerson (1995) suggests combining liability with an ex ante instrument. For invasive species, an ex ante instrument is relevant in order to foster needed prevention and 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 general marine pollution through flagging and registering a ship for ocean transportation is the context for a more focused policy on invasive species. The ship can be 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. In principle, the anticipation of the liability can be incentive enough to reduce risk of damage. However, this incentive may be less effective if polluters face limited financial liability and avoid paying damages by becoming insolvent (Sterner, 2003).

This paper addresses risk of damages and asymmetric information between the regulator and shipper in the context of two emissions vectors (ballast water and biofouling) that require more than one policy to address them. The optimal regulatory policy depends on information provided by the shipper since they know more about what abatement happens on the ship than the regulator. The difficulty of attributing damage ex post to a shipper under liability motivates the study of the efficacy of ex ante measures.

The choice of optimal regulatory policies with two vectors (ballast water and biofouling) of emissions is examined under conditions of (1) risk surrounding the potential magnitude of the damages and (2) asymmetric information between the regulating port and the shipper regarding the shipper's potential liability for any damage costs. A combination of two policies is used to address the market failures. The combination consists of liability and subsidies as well as liability and taxes.

The analysis of these policies is contrasted with an initial Case 1 that does not formally recognize both sources of emissions and possible damages. Case 2, where both sources of emissions and damages are fully accounted for, approaches reality and enables the variety of policies to be assessed for the potential to help address marine invasive species pollution. The modeling approach considers incentives for both the regulating port and the shipper facing any regulation and evaluates the optimality of possible policies for both key entities. Specifically, Case 2 contains the following components: (1) the IMO emissions standard; (2) both the shipper and regulating port realize the potential for biofouling damage that has a risk distribution; (3)

strict legal liability of the shipper for any damages; (4) a per cubic meter subsidy; (5) a fixed fee to pay for an emissions monitoring program and any necessary damage abatement costs, where the fee depends on a ship-reported estimate of the potential severity of damages, should they occur. Assuming there is asymmetric information on the potential severity of damage, should it occur, the shipper has more information than the regulator on potential the severity due to knowledge of the abatement.

Results show incentive-based policies (subsidy with liability rule or tax with liability rule) help avoid marine invasive species pollution when there are uncertain damages and asymmetric information between shippers and the regulating port. When liability is high, shipper profits are higher and social welfare is lower under regulation. Liability does not affect abatement choices, only the distribution of rents. Subsidies and taxes achieve the same level of abatement and welfare. While shipper profits are slightly lower with profits, damages are significantly lower.

2. Model of Ship and Port Regulator

The model takes the IMO standard on ballast water emissions to the ocean as a given policy 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. The environmental goal of the IMO standard is a numerical goal of risk reduction in a safety-first manner, focused on ballast water emissions.

The regulating port minimizes total social costs of shipping including any potential environmental costs subject to meeting the IMO standard. The shipper maximizes 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.

Two cases are modeled. In the first model, biofouling emissions are imposed on the IMO ballast water standard. Then, the shipper chooses the amount of ballast water emissions to release to the ocean to meet the IMO standard at least cost. Without biofouling damages formally accounted for in setting the standard, the shipper's choice matches the regulator's socially-optimal (second-best, 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" of uncontrolled invasive species. This model allows for (1) the possibility of both ballast water emissions and biofouling emissions with damages in formulating the regulations and (2) asymmetry regarding estimates of the shipper's potential liability for any invasive species impacts. Thus, this model provides a realistic description of most pollution regulation decisions. The regulatory instruments to be tested in this model include liability, subsidies and taxes. The subsequent sections derive sequentially the optimal emissions and policy levels. It will be shown that liability combined with subsidies has similar results as liability in combination with taxes. Functional forms are based on the empirical setting with properties for computational ease.

2.1 Case 1 with IMO Emission Standard Regulation

The shipper maximizes profits by selecting a combination of ballast water emissions $B_1$and biofouling emissions B_2 for ocean release to meet the IMO standard. Table 1 lists model symbols. Equation (2) indicates the IMO standard for ballast water augmented by adding biofouling emissions, another vector of invasive species released by ships to the ocean.

The model is developed on a "per cubic meter of emissions" basis to indicate a volume measure for aqueous emissions commonly used in the maritime shipping context, containing an amount (percentage) of invasive species. Equation (1) indicates that the shipper maximizes profit per cubic meter of emissions, π, by choosing to release to the ocean some amount of ballast water emissions B_1 in the tank and volume of biofouling emissions B_2 attached to the ship hull. Prior to release to the ocean, ballast water treatment onboard serves to filter and remove invasive species in the ship's emissions. Since marine invasive species can be sessile as well as suspended in aqueous emissions, biofouling consists of the volume of invaders attached to the ship as it moves from one port to another with wet weight not dry weight. It is necessary to also measure this vector of emissions in cubic meters from which sessile invaders can be filtered and removed. Prevention to address both emissions will be discussed later.

Equation (2) describes the IMO constraint on invasive species released to the ocean from ship emissions. Equation (2) describes the fixed-proportions relationship that exists between the emissions vectors and the standard $\bar{I}$. The IMO standard, $\bar{I}$, is set at a numerical limit of 0.02 that is based on a percentage of invasive species (allows for various species and sizes) (Ambroggi, 2004). While the IMO 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). The shipper's profit maximization problem is:

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

(2) subject to: $a_1B_1 + a_2B_2 \leq \bar{I}$

Non-negativity constraints on B_1 and B_2 are: $B_1 \geq 0$ and $B_2 \geq 0$. Parameter r in equation (1) is the shipper's transportation profit margin per cubic meter of emissions. In this manner the shipper's earnings can be tied to the transportation activity he performs separately from the trade revenue. This distinction helps to investigate the transportation realm where r is the monetary value multiplied by the amount of invasive species emissions released to the ocean from the tonnage transported. 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 invasive species emissions produced (and released) when the current shipping of the port is r in a manner that has been modeled in the environmental economics literature by Forster (1973). In this case, V is made up of both B_1 and B_2, according to $V=B_1+B_2$.

The shipper's profit margin, r, is approximately $0.27 per cubic meter of emissions carried by the ship (Helling and Poister, 2000).

Parameters a_1 and a_2 in equation (2) represent the percentage of invasive species per cubic meter of biofouling and the percentage of invasive species per cubic meter of ballast water emissions, respectively. Fofonoff et al. (2003) indicate reference values for both a_1 and a_2 based on time series data of the percentage of invasive species per cubic meter of ballast water and hullfouling emissions. Parameter a_1 is 0.35 percent per cubic meter of ballast water emissions, based on the typical dry weight of invasive species in the liquid volume of ballast water emissions (Ruiz and Carlton, 2003). Parameter a_2 is 0.18 percent per cubic meter of biofouling emissions.

The cost parameters c_1 and c_2 in equation (1) are the costs to filter, remove and release the invasive species per cubic meter of ballast water emissions (c_1) and biofouling emissions (c_2), respectively. Shipper's 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). Fouling growth creates enough friction, or "drag" to slow boats and increase fuel consumption, in some cases by 30% (Younqlood et al. 2003). 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 emissions (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 sealants 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 adjusted to annual figures using a discount rate of 5% for an equipment lifetime of 10 years. The 10 years lifetime is determined by the assessment of duration of effectiveness by Johnson and Miller (2002). The fixed costs are proportional to cubic meters of emissions since they are based on flow capacity. Then, it is possible to sum variable and fixed costs in the per cubic meter estimate of costs.

The cost of ballast water emissions, $c_{1,}$ is approximately \$2.38 per cubic meter of emissions, the midpoint of a range of a couple technology choices, that imply emissions are gleaned thereby lowering the concentration of invasive species. 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., 2002)]. 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 glean the volume of ballast water emissions, where the fixed costs are adjusted through discounting over the equipment lifetime to combine with variable costs by applying a 5% discount rate and an equipment lifetime of 20

[1] Parameter values indicate the estimate of biofouling emissions per cubic meter is an average of the range of biofouling treatment costs reduced by the fuel economy savings.

years. The lifetime is referenced from Taylor et al. (2002). These fixed costs are proportional to cubic meters of emissions.

The linear constraint in equation (2) that adds both types of emissions (sessile organisms from the ship hull and suspended organisms in ballast water) arriving at the port facing the IMO standard is aligned with trend evidence from Fofonoff et al. (2003) and implies a corner solution where one of the two decision variables is positive as determined by the relative values of the parameters c_1, c_2, a_1 and a_2. When $r-a_1/c_1 < r-a_2/c_2$ (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):

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

The firm chooses to use $B_2^0 = 0.11$ cubic meters of biofouling emissions (and zero percent of ballast water) to meet the IMO standard $\bar{I}$, given that there is incentive to cut down on drag weight from growth on the ship hull that demands additional fuel. Eventually, fouling growth leads to damage to hull and vessel deterioration (Rolland and DeSimone, 2002). These effects would be another incentive on the part of shippers to implement some action to prevent fouling as a vector of marine invasive species. Without emissions from both vectors, both the firm and the regulating port focus on biofouling emissions to meet the IMO standard, at least cost.

2.2 Case 2 with Regulation Accounting for Dual Vectors of Biofouling and Ballast Water Emissions

This case considers the shipper's ex-ante decision on emissions and the regulating port's ex-ante decision for regulating the *potential* for dual vectors of emissions (biofouling and ballast water). The IMO standard in equation (2) was set based only on damages from ballast water emissions (IMO, 2004). Therefore, the following model includes quadratic damage costs from biofouling emissions explicitly in addition to damages from ballast water emissions accounted for in the IMO standard. The damage costs of biofouling do not overlap with the content of equation (2) where the standard is set based on ballast water emissions only. The biofouling added in equation (2) indicates the typical dry weight amount if one attempts to divide between two sources of invasive species: ballast water and biofouling.

The regulating port defines expected social welfare E(W) as expected shipper profits less invasive species damages. The explicit specification here of biofouling damages compensates for the fact that equation (2) was not set with consideration for biofouling damages, only those of ballast water. So, the previous section was an attempt to augment the standard by including biofouling. However, biofouling damages had not been formally measured in that case. Ex-post estimates of the invasive species damages are measured per cubic meter of biofouling emissions and are quadratic in B_2, that is, invasive species damages per cubic meter of biofouling emissions as $D \cdot (B_2)^2$ with an exponential probability distribution. An index of invasive species damage, D, indicates damage to native shellfisheries which have commercial and recreational 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 [(Department of Fisheries and Oceans Canada, 2002), (Estado de Baja, 2003), (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 Alaska Dept. of Fish and Game (2002), Department of Fisheries and Oceans Canada (2002), EDAW, Inc. (2003), Estado de Baja (2003), Hanemann (2003) are 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.

The mid-point of the range of ex-post damage cost estimates is \$0.11 per cubic meter of biofouling emissions. This midpoint serves as the regulating port's ex-ante estimate of mean damage costs per cubic meter of biofouling emissions. Mean damage cost corresponds to the actual amount of biofouling emissions, $B_2^0 = \frac{\bar{I}}{a_2} = 0.11$, and enables solving for the mean value of the damage severity index, denoted $\overline{D}$, as: $\$1.00 = \overline{D} \cdot (B_2^0)^2 = \overline{D} \cdot (0.11)^2 \Rightarrow \overline{D} = 82.64$. The 0.11 is damage 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, $\lambda = 1/\overline{D}$ = 0.0121, based on initial estimates of the biofouling emissions damages to native shellfisheries, commercial and recreational values (in U.S. dollars) in Mexico, U.S. and Canada. The probability density function from the exponential distribution and quadratic damages 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. The biological basis is from Williamson and Fritter (1996) who developed a statistical or probability based approach for characterizing the outcomes of an invasion known as the tens rule where, over various steps of a possible biological invasion, each step has a one in ten probability of leading to ultimate invasion (from initial dispersal, arrival, spread, establishment, damage). This rule is thought to be applicable to marine invasive species by several marine scientists [(Ruiz and Carlton, 2003) and Orr (2003)].

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:

$$(4)\quad \max_{B_1,B_2} E(W) = \int_0^{\infty}\left[r(B_1+B_2) - c_1B_1 - c_2B_2 - DB_2^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

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

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

$$(5)\quad \max_{B_1} E(W) = \int_0^{\infty}\left[r(B_1+B_2) - c_1B_1 - c_2\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right) - D\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right)^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD,$$

the first order condition for the problem is:

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

or, defining $M_1 \equiv r + c_2(a_1/a_2) - c_1$, 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:

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

Equations (7) and (8) take into account damages, costs and relative contributions of ballast water emissions and biofouling emissions into the adjusted IMO limit, instead of one emissions vector. The port's optimal value of B_2 is obtained via the IMO pollution regulation constraint:

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

2.2.1 The Role of Liability

The form of shipper's liability is joint and several liability arising from shipping registration. Shippers are parties to the share of costs that lies between zero and one (a percentage), and the shipper's expectation is that the share is α. This share can be viewed as the probability of damage detected being attributed to the shipper to assume liability. Without ex ante 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(π), subject to the IMO regulation constraint and its anticipated share of any multiple externality damages. Given the parameters, the shipper bears damage costs αDB_2^2, contingent on the probability of pollution, and this is subtracted from the previous profit maximization. The revised profit maximization is shown in the appendix.

As the shipper's anticipated liability share α decreases, the new abatement value of $\hat{B}_1$ decreases and $\hat{B}_2$ increases, deviating from the socially-optimal values for treatment of B_1^* and B_2^* derived previously. Thus, strict liability encourages precaution when there is a risk of damages. Joint and several liability may result in less than optimal control 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 after July 1, 2004 (IMO, 2002), could emphasize that ships maintains pollution control in order to be able to engage in shipping activity.

2.2.2 Use of a Subsidy Incentive Policy

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 gleaning technology (U.S. Coast Guard, 2004). 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 and the regulating port regarding α. The shipper's *true* anticipated liability share α_t is known only to the shipper from filtering and removal efforts. 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 shipper profits. This is a 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

[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.

subsidy[3] S (derived in the appendix) to ensure that the shipper reports its true anticipated liability share.

The difference between these values and those in equation (10) is that the subsidy in the numerator of B_1 will mean more emissions are filtered and removed before release since the marginal savings to the shipper from the amount of ballast water emissions and biofouling emissions is equal to the contribution to the emissions target, taking into account the subsidy.

The port determines the per-unit ballast water subsidy rule $s(\alpha_r)$ necessary to ensure optimal abatement B_1^* under the assumption that the lump-sum subsidy $S(\alpha_r)$ 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). The ideal regulation is one with incentive (expected profit) for the shipper to reveal the truth.

The per unit subsidy offered for the shipper to abate works assumes the shipper knows that this is used to determine the lump sum subsidy. It is plausible since the lump sum subsidy programs of the U.S. Coast Guard are announced to shippers based on some form of cost sharing. This lump sum does not require additional terms such as the probability of auditing if the subsidy were based on verifying that the shipper had implemented the optimal B_1 and B_2.

2.2.3 Use of a Tax Incentive Policy

In this section, although optimality conditions may be the same as under optimal subsidies, the number of shippers will be lower in the long run under taxes as profits will be lower (Baumol and Oates, 1988).

[3] Since the model is parameterized on a cubic meter basis, this subsidy is drawn from the current ballast water reporting fee uniformly charged per boat to cover some administration costs (California State Lands Commission, 2003). This fee can be adjusted based on the potential severity of invasive species costs. For example, 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 $0.048-$0.21. The lump-sum subsidy S can be envisioned as a *reduction* in the ballast water fee.

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 in the Appendix, 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. Only the shipper knows the *true* liability share α_t. In addition to the per unit tax t, the port imposes a lump-sum fee F (derived in the Appendix) on the shipper to ensure that the shipper reports the true liability share. 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.

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 as shown in the Appendix.

The shipper's profit-maximizing choice of α_r under tax regulation in the Appendix shows that 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.

With parallel logic from the derivation of the subsidy, the following relates to investigation of the optimization components that depend on liability. Under the assumption that the lump-sum fee F ensures that $\alpha_r = \alpha_t$, the regulated shipper's expected profit $E(\pi(\ddot{B}_2(\alpha_t)))$ varies with the <u>*true*</u> liability share α_t.

3. Numerical Results for the Multiple Ship Externality Model

Table 2 indicates the parameter values used in the derivation of numerical results in subsequent tables (3 and 4). Table 3 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 control and an inefficiently high level of biofouling control. 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. As a result, the per-unit ballast water subsidy necessary to ensure that the firm selects the socially-optimal combination 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 3 illustrate how the shipper's ballast water emissions 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 gleans more ballast water emissions B_1, which helps reduce pollution, and gleans biofouling B_2. 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 3 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 and a lump-sum subsidy S of from \$0.02 to \$0.04 per cubic meter.

Table 4 also contains 5 panels of results with a lump sum tax and per unit tax. From panel a in Table 4, the taxes vary inversely as the per unit tax decreases, the lump sum tax increases with the increased values of α_r. Values in panels b and c of Table 4 are similar to panels b and c of Table 3. Hence, the taxes work as do subsidies to encourage a balance between B_1 and B_2. The shipper has incentive to report a small liability share from biofouling damages. Hence a large per unit tax, is chosen because the shipper will otherwise choose a low level of hullfouling gleaning to discount the damages. As the reported value of α_r increases, the increase in liability for damages is enough incentive for the shipper to choose the optimal combination of hullfouling and ballast water.

Clearly there is a difference in welfare between the two sets of instruments. Panel d in Table 4 indicates a lower profit for the shipper facing taxes rather subsidies.

4. Conclusions

The results of this study show there is potential for a combination of incentive policies to help avoid marine invasive species in situations involving risk of damages and asymmetric information between ports and shippers.

The incentive policies 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 policy. However, when shipper's liability is high, a shipper regulated under the incentive policy earns higher profits than would an unregulated firm. Changes in liability do not affect the shipper's socially-optimal selections of emissions reduction—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 policy 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 policy, 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 4), depending on the shipper's multiple emissions vectors damage liability, result in the shipper's selection of the socially-optimal combination of emissions reduction (compare panels b and c of Table 3 and Table 4). Of course, under the tax-based policy, the shipper's profits are lower (compare panel d in Table 2 with panel d in Table 4), but expected social welfare remains the same (compare panel e in Table 3 with panel e in Table 4). The tax-based model shows that the same efficiency result can be achieved in alternative ways depending on equity goals and other constraints.

The model for the analysis draws on existing policy channels for potential regulatory action to formally address both shipping vectors of marine invasive species. The IMO guideline recommendation as the emission standard used in the model is presented in the mode of offering the flexibility to the shipper to be less or equal to the amount of emission allowed. Drawing on some measures of damages pertaining to biofouling meant that a distribution of damage risk was specified to derive analytical and numerical results. However, there are other aspects to the invasive species pollution problem that are truly uncertain where there would hardly be a risk probability distribution to specify. In some cases, such as with uncertainty in determining which shipper is at fault or uncertainties in the legal process, etc, which may prevent the shipper from bearing full financial responsibility for any damage, the parameter α made sense in that it allows the possibility of a range rather than a point estimate to explore the variation in the liability policy with some uncertainty. However, with other aspects of uncertainty, the model would have to be stated with stochastic and general functional forms that may not have the definitive magnitudes in which to offer some of the interpretations found here with different policy options. This analysis can be viewed as offering a foundation for further analysis to ponder present and future policy options.

The implementation of the liability, subsidy and tax incentive policies can occur through existing but refined policies. Currently, the port fee for reporting ballast water filter and removal of emissions 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 emission reductions of the analysis in order to properly address marine invasive species through both shipping emissions vectors. The 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. Rather than a focus on hypothetical policy, the existing channels for the incentive mechanisms are studied, thereby making it more plausible that the pollution problem can be addressed from the results. Refining current policy involves: (1) tying current technology subsidies of the U.S. Coast Guard to liability; (2) Tying current ballast water reporting fee to the port security liability rule; (3) Ship registration liability under port security law post 2004 is more prominent and can help with environmental regulation of ships. U.S. Senate Bill 770 Section 1.C mentions liability as a plausible policy to assign civil penalty for not addressing invasive species introductions related to shipping in the U.S. Exclusive Economic Zone. The Invasive Species Specialist Group of the IUCN has called for the development of liability and criminal penalties for the consequence of unchecked, purposeful introductions of marine invasive species with responsibility for all costs associated with control, enforcement, and damages (Invasive Species Specialist Group, 2000).

The Ecological Society of America recommends actions that include focus on commercial shipping pathways, quantitative analysis, and study of incentives for cost-effective regulation. This research provides such action. The analytical method and policies apply to other settings beyond the Pacific Coast of North America by making appropriate modifications to choice variables, functional forms, sources of uncertainty and asymmetric information for those settings.

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Appendix 1

(9) $$\max_{B_1,B_2} E(\pi) = \int_0^{\infty}\left[r(B_1 + B_2) - c_1B_1 - c_2B_2 - \alpha DB_2^2\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

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

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

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

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^*.

The following maximization includes subsidies s and S as functions of α, that is, $s(\alpha)$ and $S(\alpha)$. 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) $$\max_{B_1,B_2} E(\pi) = \int_0^{\infty}\left[r(\overline{B}_1 + \overline{B}_2) - (c_1 - s(\alpha_r))B_1 - c_2B_2 - \alpha_t DB_2^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

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

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

(12)

$$\max_{B_1} E(\pi) = \int_0^{\infty}\left[r(\overline{B}_1 + \overline{B}_2) - (c_1 - s(\alpha_r))B_1 - c_2\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right) - \alpha_t D\left(\frac{\bar{I}}{a_2} - \frac{a_1}{a_2}B_1\right)^2 + S(\alpha_r)\right]\cdot\left(\lambda e^{-\lambda D}\right)dD$$

The FOC for the problem is:

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

The use of subsidies should result in $\overline{B}_1 = B_1^*$ or

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

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

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

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

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

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

The first order condition for this problem is:

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

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

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.

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

To verify that a lump-sum subsidy S ensures $\alpha_r = \alpha_t$, 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),

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

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

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

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(π($\overline{B}_1$)) varies with its <u>*true*</u> liability share α_t as:

(18)

$$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \int_0^\infty \left\{ M_1\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + \frac{\partial s}{\partial \alpha_t}\overline{B}_1 + s\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + M_2\overline{B}_1 + \alpha_t M_2\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] \right.$$
$$\left. - M_3\overline{B}_1^2 - 2\alpha_t M_3\overline{B}_1\left[\frac{\partial \overline{B}_1}{\partial s}\frac{\partial s}{\partial \alpha_t} + \frac{\partial \overline{B}_1}{\partial \alpha_t}\right] - D(\overline{I}/a_2)^2 + \frac{\partial S}{\partial \alpha_t}\right\}\cdot\left(\lambda e^{-\lambda D}\right)dD$$

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) $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \int_0^\infty \left\{ -D(\overline{I}/a_2)^2 + M_1\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + s\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right] + M_2\overline{B}_1 + \alpha_t M_2\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right] \right.$$
$$\left. - M_3\overline{B}_1^2 - 2\alpha_t M_3\overline{B}_1\left[\frac{\partial \overline{B}_1}{\partial \alpha_t}\right]\right\}\cdot\left(\lambda e^{-\lambda D}\right)dD$$

From section 2.2.4, it follows that $\frac{\partial \overline{B}_1}{\partial \alpha_t} = \frac{-M_1}{2\alpha_t (a_1/a_2)^2(1/\lambda)}$. Hence, 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, $$\frac{\partial E(\pi(\overline{B}_1))}{\partial \alpha_t} = \left(\frac{M_1^2}{4(a_1/a_2)^2}\right)\int_0^\infty\left\{\frac{D}{(1/\lambda)^2}\right\}\cdot\left(\lambda e^{-\lambda D}\right)dD - \left(\frac{M_1^2}{2(a_1/a_2)^2}\right)\int_0^\infty\{\lambda\}\cdot\left(\lambda e^{-\lambda D}\right)dD.$$

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:

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

The portion of $E(\pi(\overline{B}_1))$ that varies with α contains the following terms:

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

Expression (22) is equal to the integral of expression (21) multiplied by the density function of α, $p(\alpha)$, where $p(\alpha)$ is uniformly distributed over support (0,1), based on the description of liability under shipping rules facing limited liability as well as joint and several liability that yields a flexible range of possible outcomes. The integral is taken over α from $\alpha = 0$ to $\alpha = \alpha_t$, that is:

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

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

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

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

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

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

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

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 $r-(c_2\overline{I}/a_2)$:

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

For each following subsection, the results of the analysis are similar to the per unit lump sum subsidy analysis with the difference that fees represent an additional cost and subsidies, a reduction in costs.

2.2.8.1 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^*.

2.2.8.2 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^*.

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

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

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

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

The FOC for the problem is:

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

Evaluating the integral in (29) using methods analogous to previous sections, the resulting expression for the shipper's profit-maximizing values of B_1 and B_2 is solved under tax regulation, denoted $\dddot{B}_1$ and $\dddot{B}_2$:

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

2.2.8.4 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 per unit tax is similar to the form of the per unit subsidy.

2.2.9 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 $E(\pi(\ddot{B}_1, \ddot{B}_2))$. Through the first order necessary condition derived from equation (28) above:

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

The first order condition for this problem is:

(33)

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

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

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

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

Recognizing that $\frac{\partial \dddot{B}_2}{\partial \alpha_t} = \frac{-M_4}{2\alpha_t^2 (1/\lambda)}$, and evaluating the integral in expression (35) using methods analogous to those in section 2.2.1, yields:

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

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

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

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

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

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

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:

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

2.2.11 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 $r - (c_1\bar{I}/a_1)$:

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

This profit should be lower than the subsidy case.

Table 1. Model notation.

π = shipper net profits per cubic meter
r = shipper profits per cubic meter of emissions
B_1 = cubic meters of ballast water emissions
B_2 = cubic meters of biofouling emissions
c_1 = cost per-cubic meter of ballast water emissions
c_2 = per-cubic meter of biofouling emissions
$\bar{I}$ = IMO emissions standard constraint in percent of invasive species
a_1 = percent per cubic meter content of invasive species in ballast water emissions B_1
a_2 = percent per cubic meter content of invasive species in biofouling emissions B_2
s = subsidy per cubic meter
S = lump sum subsidy
α_t = shipper's true liability share
α_r = shipper's reported liability share
D = invasive species damage index
p(D) = probability density function of random variable D
λ = location parameter of exponential probability density function
$M_1 \equiv c_2(a_1/a_2) - c_1$, derived parameter
$M_2 \equiv 2D(\bar{I}/a_2)(a_1/a_2)$, derived parameter
$M_3 \equiv D(a_1/a_2)^2$, derived parameter
$M_4 \equiv c_1 a_2 / a_1 - c_2$, derived parameter

Table 2. Parameter values

Parameter	Value
r	0.65
c_1	\$2.38
c_2	\$0.07
a_1	0.35
a_2	0.18
$\bar{I}$	0.01
B_2^0	0.11
λ	0.0121

Table 3. Solution values for the multiple externality model, with subsidy incentive mechanisms.

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

	α_r = 0.5	0.75	0.99
s*	1.121944	0.560972	0.022439
S*	0.060001	0.090001	0.118802

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.53479	0.51648	0.49889
0.75	0.54701	0.53479	0.52307
0.99	0.55293	0.54367	0.53479

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.07123	0.10685	0.14104
0.75	0.04749	0.07123	0.09403
0.99	0.03598	0.05397	0.07123

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.268167	0.268167	0.268167
0.75	0.267140	0.267140	0.267140
0.99	0.266153	0.266153	0.266153

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.146110	0.145083	0.142163
0.75	0.145654	0.146110	0.145689
0.99	0.145103	0.145869	0.146110

Table 4. Solution values for the multiple externality model, with tax incentive mechanisms.

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

	α_r = 0.5	0.75	0.99
t^*	0.57700	0.28850	0.01154
F^*	0.00411	0.00616	0.00813

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.53479	0.51648	0.49889
0.75	0.54701	0.53479	0.52307
0.99	0.55293	0.54367	0.53479

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

α_t \ α_r	0.5	0.75	0.99
0.5	0.07123	0.10685	0.14104
0.75	0.04749	0.07123	0.09403
0.99	0.03598	0.05397	0.07123

Panel d.-Shipper's expected profit, $E(\pi)$, per cubic meter

α_t \ α_r	0.5	0.75	0.99
0.5	0.139945	0.139945	0.139945
0.75	0.138917	0.138917	0.138917
0.99	0.137931	0.137931	0.137931

Panel e.-Expected social welfare, $E(W)$, per cubic meter

α_t \ α_r	0.5	0.75	0.99
0.5	0.146110	0.145083	0.142163
0.75	0.145654	0.146110	0.145689
0.99	0.145103	0.145869	0.146110

Valuation for Environmental Policy: Invasive Species

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Models of Spatial and Intertemporal Invasive Species Management

by Burnett and Kaiser

3 Models/Case Studies

i) Hedonic pricing model to value invasive species damages – noise pollution from *coqui* frogs

ii) Spatial model of control – *Miconia calvescens*

iii) Spatial model of early detection and control – *Boiga irregularis* (Brown Treesnake)

Relatively few spatial economic models of invasive species management

- Huffaker, Bhat and Lenhart (1992) examine how dispersal between 2 sites affects control and the invasion size
- Brown, Lynch and Zilberman (2002) examine a static model of spatial control with dispersal from a source located some distance from agricultural production. They focus on source control and barrier zones as a means of reducing invasive species impacts.
- Sharov and Leibhold (1998), Sharov, Leibhold and Roberts (1998) and Sharov (2004) examine the use of barrier zones to slow the spread of an invasive species. “Slow the Spread” program used to manage the gypsy moth in N. America.
- Several ongoing efforts under USDA’s PREISM program

Invasive species management is complicated

- spatial considerations (control costs, damages, dispersal)

- intertemporal considerations – current control costs mitigate current and future damages – damages caused by invasion growth

Most research focuses on static models or steady-state analysis of a dynamic, homogeneous invasion

Very few careful case studies consider spatial and dynamic considerations

Burnett and Kaiser provide a useful step in this direction

Typology of optimal control models:

- dynamic, homogeneous invasion
- static, spatial
- dynamic, “parametric” spatial interactions
- dynamic, fully endogenous spatial interactions

Dynamic, homogeneous invasion

$$\min \sum_{t=0}^{\infty} \delta^t \left[c(n_t) x_t + D(n_t) \right] \quad \text{subject to: } n_{t+1} = n_t + g(n_t) - x_t$$

Optimal steady state (necessary conditions):

$$c(n) = \frac{D'(n) + c'(n)g(n) + c(n)g'(n)}{r}$$

mar. cost of control = mar. benefit of control compounded at rate r indefinitely

mar. benefit = marginal damages avoided adjusted by the effect a change in the invasion size has on control costs

Burnett/Kaiser spatial model (discrete time version)

$$\min \sum_{t=0}^{\infty} \delta^t \sum_{i=1}^{k} \left[c_i(n_{it}) x_{it} + D_i(n_{it}) \right] \qquad \text{s.t. } n_{it+1} = n_{it} + g_i(n_{it}, n_t) - x_{it}$$

$n_t =$ total invasion size

influences control cost, damages and growth in patch i

Optimal steady state (necessary conditions):

$$c_i(n_i) = \frac{D_i'(n_i) + c_i'(n_i) g_i(n_i, n) + c_i(n_i) \dfrac{\partial g_i(n_i, n)}{\partial n_i}}{r}$$

Total invasion size affects management in patch *i* parametrically (each patch is “small” relative to whole)

Complete spatial, dynamic model

$$\min \sum_{t=0}^{\infty} \delta^t \sum_{i=1}^{k} [c_i(n_{it})x_{it} + D_i(n_{it})] \quad \text{s.t. } n_{it+1} = n_{it} + g_i\left(n_{it}, \sum_{i=1}^{k} n_{it}\right) - x_{it}$$

Optimal steady state (necessary conditions):

$$c_i(n_i) = \frac{D_i'(n_i) + c_i'(n_i)g_i(n_i,n) + c_i(n_i)\dfrac{\partial g_i(n_i,n)}{\partial n_i} + \sum_{j=1}^{k} c_j(n_j)\dfrac{\partial g_j(n_j,n)}{\partial n}}{r}$$

Control in patch *i* has non-negligible effect on future control costs in other patches

One note of caution:

Models of invasive species management are similar to models of renewable resource management, with one important difference. Renewable resources provide social benefits while invasive species impose social costs.

A larger renewable resource biomass is associated with a larger opportunity set for social welfare

In contrast, a larger invasion size is associated with a smaller opportunity set for social welfare

Economic models of renewable resources typically maximize a concave objective function subject to a concave transition function (resource growth function)

Economic models of invasive species minimize social costs subject to the transition function that governs growth and spread in the invasion size

Since all invasions are bounded, the transition function is necessarily non-convex. Hence, commonly used second-order conditions are not automatically satisfied. Invasive species management problems are potentially non-convex.

Brown Treesnake – Early detection and rapid response

Divide an island into K cells

A model of “search and destroy”

When to treat each cell, given invasion size and proportion of cells treated in previous period?

Potential extensions:

Extend spatial analysis to incorporate endogenous spatial interactions – effect of patch *i* on growth in other patches – neighborhood dispersion (vs. long distance dispersion)

Adaptive management and uncertainty – treatment in cell *i* provides information about invasion size in other cells that can be used to inform future policy choices

Economic analysis of surveillance and monitoring

Economic Evaluation of Policies to Manage Aquatic Invasive Species   by Linda Fernandez

Invasive species management can be improved by identifying pathways of introduction and directing policy toward those pathways

A major pathway of aquatic introductions is maritime shipping – ballast water and/or biofouling

Potential for strategic interactions – mitigation by one agent (port or shipper) affects incentives for other agents

Models of aquatic "biological pollution":

- Shippers maximize profits subject to emission limit. Linear programming model of ballast water and biofouling emission reductions.

- Uncertain damages from biofouling. Port maximizes shipper profits less expected damages subject to emission limit.

- Shippers face liability for damages. Asymmetric information. Ports use a combination of fees and subsidies/taxes to induce shippers to reveal true liability and to choose port's target emissions

Extensions:

Mitigating risk associated with pathways is dependent on technology.

Exs: Ballast water management and biofouling
Wood packing material (ISPM N. 15)

Can policy be used to bring about better technology to manage pathway risk?

Relationship between policy and induced technological change in the context of invasive species.

Institutional barriers

International Convention for the Control and Management of Ships Ballast Water & Sediments was adopted in February, 2004.

Entry into force 12 months after ratification by 30 States, representing 35% of world merchant shipping tonnage

As of March 31, 2007, 8 States (3.2% of tonnage) had ratified.

States raised concerns about liability in relation to the Convention on Biological Diversity

International invasive species problems involve repeated interactions between self-interested parties (international trade).

Literature on repeated games suggests that cooperation may be sustainable when the payoffs to all parties exceeds their minimax payoff.

A better understanding of the circumstances under which cooperation is a sustainable equilibrium for invasive species management is needed.