The Economic Impacts of Aquatic Invasive Species: A Review of the Literature

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Invasive species are a growing threat in the United States, causing losses in biodiversity, changes in ecosystems, and impacts on economic enterprises such as agriculture, fisheries, and international trade. The costs of preventing and controlling invasive species are not well understood or documented, but estimates indicate that the costs are quite high. The costs of aquatic invasive species are even less well understood than those for terrestrial species. A systematic approach is needed to develop a consistent method to estimate the national costs of aquatic invasives. This review of the economic literature on aquatic invasive species is the first stage in the development of that estimate. We reviewed over sixty sources and include both empirical papers that present cost estimates as well as theoretical papers on preventing and mitigating the impacts of aquatic invasive species. Species-specific estimates are included for both animals and plants.

Key Words: aquatic invasive species, costs, literature review

Invasive species are a growing threat in the United States, causing losses in biodiversity, changes in ecosystems, and impacts on economic enterprises such as agriculture, forestry, fisheries, power production, and international trade. An invasive species is a species that is "non-native to the ecosystem under consideration and ... whose introduction causes or is likely to cause economic or environmental harm or harm to human health" (Executive Order 13112, Appendix 1, 1999).[1] Not all non-native or non-indigenous species (NIS) become invasive. Some fail to thrive in their new environment and die off naturally. Others survive, but without destroying or replacing native species. Most introduced species do not meet the standards defined in Executive Order 13112 as "invasive" [U.S. National Invasive Species Council (NISC) 2000]. However, those that do meet the definition have the ability to cause great harm to the ecosystem.

The means and routes by which species are introduced into new environments are called "pathways" or "vectors." Some species that become invasive are intentionally imported and escape from captivity or are carelessly released into the environment. Other invasives are unintentionally imported, arriving through livestock and produce, or by transport equipment such as packing material or a ship's ballast water and hull. Fish and shellfish pathogens and parasites have been introduced into the United States unintentionally and intentionally in infected stock destined for aquaculture and aquarium trade. Crates and containers can harbor snails, slugs, mollusks, beetles, and other organisms. Nearly 51.8 percent of maritime shipments contain solid wood packing materials, and infection of these materials is substantial [Animal and Plant Health Inspection Service (APHIS) 2000]. Military cargo transport may also harbor unintended species. Stimulated by the expansion of the global transport of goods and peo-

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[1] For a full description of the Executive Order, see http://www.inva[-]sivespecies.gov/laws/main.html.

ple, the numbers and costs of invasive species are rising at an alarming rate (NISC 2001). The cost of preventing and controlling invasive species is not well understood or documented, but estimates indicate that they are quite high, in the range of millions to billions of dollars per year [Office of Technology Assessment (OTA) 1993, Pimentel et al. 2000].

While several studies document prevention, management, and control costs for specific invasive species, there are no comprehensive national or regional estimates of their economic impact, particularly for aquatic invasive species (AIS) as a group. The federal government is interested in the scale of the impacts of AIS relative to other environmental concerns in order to best address the issue. The U.S. Environmental Protection Agency (EPA) held a workshop in July 2005 to address the lack of a comprehensive national estimate or regional estimates of the economic impacts of aquatic invasive species. This workshop focused on ideas for conceptual frameworks and analytical tools for estimating national and regional aquatic invasive species economic impacts. This review of the economic literature on aquatic invasive species provides an introduction to the currently available estimates of impacts, what methods might be useful for developing national or regional estimates, and a look at methods for determining the most effective management strategies.

In general, this review is limited to studies dealing specifically with aquatic or aquatic-related species and does not include estimates of the costs of purely terrestrial species. Both theoretical and empirical studies are included in this review although the theoretical studies are included only if they have general principles or potential applications to AIS. Based on the limited amount of research to date, the studies are not easily grouped together by common themes or species. We have grouped them here under theoretical research, trade-related studies, general cost estimates, and then empirical studies by major aquatic taxonomic groups. Dollar figures in both the text and Table 1 have been adjusted from their original sources to 2003 dollars using the annual average CPI index (U.S. Bureau of Labor 2005).[2]

[2] If the original study did not state what year dollar values were measured in, we used the year of publication to index the values.

Theoretical Research

Very few studies specifically on aquatic invasive species exist in the formal economics literature. Those available primarily concentrate on theoretical considerations with little empirical analysis, let alone at a national scale. Obtaining a national cost estimate involves issues of uncertainty, public goods, risk, multiple sources, and impacts. A number of papers concentrate on issues related to trade. Others develop models of the risk of invasive species or incorporate both ecological and economic models.

Evans (2003) provides a good general introduction to the economic issues, by pointing out that the causes of biological invasions are often related to economic activities. He classifies the impacts of invasives into five types related to production, price and market effects, trade, food security and nutrition, and financial costs. Perrings et al. (2002) discuss how invasions result from decisions on land use, the use of certain species in production or consumption, and global movement of people and products, and how property rights, trade rules, and prices often influence these decisions. As a result, control of invasive species is a public good and is only as good as the weakest provider of control. If even one nation or state does not provide adequate control, a species can spread and cause damage to all. This calls for a coordinated response among affected parties.

The intentional and unintentional pathways of invasion in the aquatic environment have risk probabilities over time and space that may be known or unknown. Shogren (2000) incorporates economics into a model of endogenous risk for invasive species. The risk from invasive species may be reduced from either mitigation (measures to prevent and reduce the likelihood of invasion) or adaptation (behavioral responses to limit valuable consequences from introduction, establishment, or spread of invaders without changing the likelihood that they will invade). The model shows that a higher risk of invasion directly increases adaptation, but the effect on mitigation may be positive or negative. Indirect effects on both adaptation and mitigation depend on whether or not mitigation and adaptation are substitutes or complements. Horan et al. (2002) address pre-invasion control of AIS using risk management models as well as with an uncertainty/ignorance

Table 1. Summary of Selected Studies Providing Empirical Estimates (in 2003 dollars)

Authors	Time Period Covered	Species/Pathway	Geographic Area	Dollar Value	Outcomes
General Estimates					
OTA (1993)	1906–1991	79 harmful invasives including sea lamprey, zebra mussel, Asian clam, salt cedar, purple loosestrife, melalluca, and hydrilla	U.S.	Total cumulative damage \$131–185 billion; 3 harmful fish \$631 million; for 3 aquatic invertebrates \$1.6 billion; and \$135 million/annually for aquatic plants	Both economic and ecological damages caused by invasives
Pimentel et al.[a] (2000)		Wide range of species including mammals, birds, amphibians, fish, mollusks, and plants	U.S.	\$147 billion annually for the U.S. (2000); \$128 billion annually for the U.S. (2005)	Review and analysis of selected literature
Fernandez (2006a)	2003	Ballast water		Optimal abatement strategies applying subsidies of 0.5 to 30 cents per cubic meter and a lump sum fee of 0.10 to 0.18 cents	Examines different incentive mechanisms that can be applied to ships to help ports with unintended consequences of NIS
Younqlood et al. (2003)	2000–2002	Hull fouling	Pacific	30% increase in fuel costs per use	The weight of the attached species causes drag and requires more fuel to travel same distance
Animals					
GAO (2000)	1999	Sea lamprey	New York and Michigan	\$304,000 (NY); \$3.3 million (MI) annually	
Jenkins[a] (2001)		Sea lamprey	U.S. and Canada for Great Lakes	\$13.5 million annually	
Lupi, Hoehn, and Christie (2003)	2003	Sea lamprey	St. Mary's River	\$4.2 million per treatment	Lampricide
Lupi, Hoehn, and Christie (2003)	2003	Sea lamprey	St. Mary's River	\$300,000 per year	Sterile male release and trapping
Lupi, Hoehn, and Christie (2003)	2015	Sea lamprey	St. Mary's River	\$3.2–\$5.8 million total in 2015	Benefits of control for Michigan anglers
OTA (1993)		Sea lamprey		\$675 million annually	Lost fishing opportunities and indirect economic impacts of terminating control

cont'd.

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Authors	Time Period Covered	Species/Pathway	Geographic Area	Dollar Value	Outcomes
Animals **(cont'd.)**					
Sturtevant and Cangelosi (2000)[a]		Sea lamprey	Great Lakes	\$2.1–\$4.3 billion/year	Benefits of control programs
Hushak (1997)	1985–1995	Ruffe	Lake Erie	\$724 million cumulative	Estimated losses to sport fishery
Jenkins (2001)[a]		Ruffe	Great Lakes	\$520,000 annually	Losses for native fisheries
Leigh (1998)[a]		Ruffe		\$13.6 million cumulative	Estimated total cost of 11-year control program
Leigh (1998)[a]		Ruffe		\$119 million to \$1.05 billion cumulative	Benefits of control programs to sport and commercial fishing
Lafferty and Kuris (1996)	1990–1991	European green crab	California, Pacific Northwest	\$22.8 million for northern and central California, \$4.9 million for southern California, and \$59 million for Puget Sound (projected)	Commercial value of Dungeness and rock crabs, mussels, oysters, and bait reduced for market
Armour, Tsou, and Wiancko (1993)[a]		Zebra mussel	Great Lakes	\$127 million annually	Costs to approximately 46 power plants
Cataldo (2001)[a]	10 years	Zebra mussel	Great Lakes	\$3.2 billion over 10 years	
Hushak and Deng (1997)	1992–1994	Zebra mussel		\$10.9 million annually	Research expenditures
Hushak, Deng and Bielen (1995a)[a]	1989–1994	Zebra mussel	Great Lakes, tributaries and inland waters	\$509,000 total for period	Monitoring and control costs for 125 industrial facilities
O'Neill (1997)	1989–1995	Zebra mussel	35 U.S. states and 3 Canadian provinces	\$83 million and a mean of \$248,000 per facility	Total expenditures of 339 facilities
O'Neill (1997)	1995	Zebra mussel		\$21.5 million	Total annual costs for 339 facilities
Park and Hushak (1999)	1989–1994	Zebra mussel	Great Lakes	\$149 million total for period or \$37 million annually between 1992 and 1994	Based on a survey of 142 facilities
Ruetter (1997)[a]		Zebra mussel	Great Lakes	\$400,000–\$460,000 annually	Estimated control costs of average large water user
Sun (1994)	1990–2000	Zebra mussel	Great Lakes	\$6.5 billion over 10 years	U.S. Fish and Wildlife estimate

cont'd.

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Authors	Time Period Covered	Species/Pathway	Geographic Area	Dollar Value	Outcomes
***Animals* (cont'd.)**					
U.S. Geological Survey (as cited in Jenkins 2001)[a]		Zebra mussel	Great Lakes	$92,000 per plant per year (hydroelectric); $160,000 per plant per year (fossil-fuel); $908,000 per plant per year (nuclear plants)	U.S. Geological Survey estimates
OTA (1993)	Early 1980s	Asian clam	U.S.	$10 million compliance costs and $2.2 billion total in annual losses	Compliance costs are for nuclear electric industry only
Marsa (2002)	2002	*Bugula neritina*	California	$376,390 per pound of finished product	Pharmaceutical value
Fernandez (2006b)	2002	Nemertean worm	Alaska/Canada	$425,480 per cubic meter	Welfare change due to reduction in commercial red king crab
Plants					
Cesar, Vanbeukerling, and Prince (2002)	2001	Green algae	Maui, Hawaii (16 miles of coastline)	$9.8 million property loss, $11.2 million in reduced occupancy, and $1.9 million of tax loss annually	Damages in an area supporting tourism
Bell and Bonn (2004)	2003–2004	Hydrilla	Florida	$857,000 in lost recreational value annually	Estimated potential impacts on agriculture, flood control, and residential property values
Padilla and Williams (2004)	2000–2001	*Caulerpa taxifolia*	Southern California	$4.3 million over two years	Early response removal and monitoring program
Pimentel et al. (2000)[a]		European loosestrife		$48 million annually	Estimated control costs and forage losses
Rockwell (2003)[a]		Aquatic weeds	U.S.	$1–$10 billion annually	National impacts
Thunberg, Pearson, and Milon (1992)	1991	Aquatic plants	Florida	$10 million annually	Avoided flood damages to residential structures
Thunberg and Pearson (1993)	1992	Aquatic plants	Florida	$6,345 per acre	Avoided flood damages to citrus crops
Zavaleta (1999)	1998	Tamarisk	Lower Colorado River (U.S.)	$137–$370 million annually	Water supply and flood damages

[a] Time period covered is ambiguous; date of publication used for indexing dollar values.

framework. Because invasions exhibit a low probability of occurring, often have catastrophic consequences when they do occur, and tend to be irreversible, these type of models and frameworks are thus better suited for analyzing strategies of pre-invasion control than traditional expected utility theory.

Thomas and Randall (2000) investigate how information and irreversibility affect management of NIS through intentional introductions. They analyze the posting of bonds equal to the estimated cost of repairing any future damage that could occur in the worst-case scenario of intentional introductions. The success of the strategy depends on setting the appropriate bond level and balancing the true cost of dealing with worst-case disasters when they arise, as well as the profit level of the proposed business and the ability of a business enterprise to absorb the costs.

Barbier (2001), Knowler and Barbier (2000), and Knowler (2005) develop and apply a model of an aquatic invasive species when there is competition between the invader and a native species. The two principles of the model are that the effects of the invader depend on the exact nature of the interaction and that the correct comparison for determining effects is an ex-ante and ex-post invasion scenario. The model can accommodate diffusion, competition, or predation, and is applied to a case study of a comb-jelly in the Black Sea.

Leung et al. (2002) develop a stochastic dynamic programming model that incorporates both ecological and economic factors, evaluates risks, and quantifies the relative benefits of prevention and control strategies for aquatic invaders. The model is applied to the case of zebra mussels inhabiting a single Midwestern lake. For a given probability of reducing invasions, the model can determine the point at which the prevention costs equal the benefits.

Olson and Roy (2002) examine the control after an invasion whose natural growth and spread is subject to environmental disturbances, outlining conditions under which it is optimal to eradicate or not. Eradication depends on the tradeoff between the discounted expected intrinsic growth rate and the marginal costs of removing the entire invasion. They find that if a small invasion produces damages compounded indefinitely that are greater than the marginal costs of eliminating the invasion, eradication is always preferred. The opposite is true if damages are less than marginal costs.

Trade-Related Studies

Trade provides a major conduit for the introduction of invasive species (Ruiz and Carlton 2003). Species "hitchhike" on commodities, packing materials, and transport vessels, especially ships.[3] The World Wildlife Fund (WWF) estimates that as many as 4,000 different species can hitchhike in typical ships' ballast at any one time (Planet Ark 2004). Expanding volume and diversity of trade are seen as having contributed to the growth of invasives in the United States.

Establishing a definitive link between NIS and trade is not easy, and there have been few attempts to quantify this link. Levine and D'Antonio (2003) attempt to forecast the rate of future invasion by examining the historical relationship between international trade and the level of established non-native species in the United States.[4] They relate past merchandise trade to the accumulated number of three groups of non-native species (insects, plant pathogens, and mollusks). The authors predict that as a result of projected international trade between 2000 and 2020, the number of established species in these three groups will increase by 16 to 24 percent from those present in 2000. Mollusks are predicted to increase 4 to 36 percent. The paper notes that these values represent less than twice the number of observed invasions over the 20-year period between 1960 and 1980. Over that time, imports were roughly 10 percent of the amount forecasted for the next twenty years. This would imply that while the rate of introductions may slow, the total number of NIS is likely to increase. Thus, if the 10 percent rule is applied, the burden on society, even looking at the lower bound of the estimates, is likely to be large (Williamson and Fritter 1996).[5]

[3] More infamous examples of hitchhiking species include the zebra mussel (*Dreissena polymorpha*) and the Asian clam (*Corbicula fluminea*).

[4] The three models were log-log species area, log-linear species area, and Michaelis-Menten.

[5] The rule of thumb is that 10 percent of the species introduced will become invasive.

Studies on Marine Shipping

Accepting that there is a link between trade and non-indigenous species, what is the most likely vector for their introduction? Those studies that do look at pathways tend to focus on transoceanic shipping as the most likely vector for invasives, especially aquatics (Ruiz and Carlton 2003, Krcmar-Nozic, Van Kooten, and Wilson 2000).

Fernandez (2006a) examines the conditions under which various invasive species management programs are optimal given the goal of the regulating port to minimize social costs of shipping, including any potential environmental impacts. Fernandez shows that by applying an incentive mechanism consisting of two subsidies (one based on per unit ballast water and the other a lump sum), and depending on the shipper's anticipated liability share of the damage, a socially optimal mix of ballast management and biofouling management can be achieved to address two externalities. Fernandez generates empirical estimates for ballast water management and biofouling management for the Pacific coast of North America from general references found in Taylor et al. (2002) and Johnson and Miller (2003). Abatement of ballast water is conducted in more effective ways than ballast water exchange, such as (i) heat-in-transit practices, (ii) ultraviolet treatment, (iii) filtration, (iv) ozonation, and (v) deoxygenation, according to Taylor et al. (2002) and Langevin (2003).

In February 2004, a new international ballast water convention was adopted. This International Convention for the Control and Management of Ships' Ballast Water and Sediment will enter into force 12 months after ratification by 30 countries representing 35 percent of the world's merchandise shipping tonnage. The convention states that parties agree to "prevent, minimize and ultimately eliminate the transfer of harmful aquatic organisms and pathogens through the control and management of ships' ballast water and sediment" [International Maritime Organization (IMO) 2005]. Fernandez (2006a) accounts for this IMO convention by addressing ballast water and hull fouling vectors of invasive species.

Horan and Lupi (2005a, 2005b) examine the economic efficiency of several compliance strategies in addition to ballast water exchange (BWE). The first paper (2005a) argues that the characteristics of marine bioinvasions complicate the traditional process of applying emission-based approaches (standards or incentives) to the problem. The extremely variable nature of invasions as well as the limitations of current technology to detect the source of an invasion make it nearly impossible to determine which vessel is a potential or actual carrier of an invader. This makes both prevention of invasions and enforcement of traditional emission controls problematic. The paper compares costs, participation rates, and the probability of invasion for various subsidy strategies and technology options. Ballast water exchange, heating, and filtration technologies are compared for the prevention of three potential new invaders into the Great Lakes. The second paper (2005b) suggests tradable permits for ballast water, using data for the Great Lakes.

Studies on Policy Responses

Is there an effective way to manage general trade flows so as to reduce the risk of invasives entering the country? Quarantine and import bans have been the favored methods over the years (Jenkins 1996). However, the cost of these restrictions, including the loss in consumer surplus, must be considered. There are several studies which look at optimal policy responses to trade in light of these factors.

Costello and McAusland (2003) and McAusland and Costello (2004) examine specific rules for trade and invasives, given expected damage, rate of infection in imports, and changing production costs of foreign suppliers. The Costello and McAusland (2003) paper serves as a "first pass" at establishing a theoretical relationship between invasive-related damage and patterns of trade and protectionism. The paper asserts that barriers to trade are more likely to backfire as a means of preventing damage from exotic species when the country in question is an importer of agricultural goods, when the country's citizens are in a high income group and so demand for agriculture goods is price insensitive, and when there is substantial potential for domestic agriculture to expand in response to high local prices.

A central discussion point in Costello and McAusland (2003) is that if we treat damages arising in agriculture as a proxy for overall costs related to invasives, we may misjudge not only the magnitude of these costs but other qualitative effects that trade policy has on the problem. Finally, Costello and McAusland (2003) provide a host of extensions to examine how the optimal policy mix is affected by changes in the structure of trade and production patterns.

McAusland and Costello (2004) examine substitutability and complementarities between two policy tools aimed at minimizing introductions. The two policies are tariffs and inspections. A Pigouvian tax on imports is part of the first-best solution that would internalize the NIS externality caused by trade. Unless perfect inspections are costless, trade is a problem and so should be taxed. Inspections make trade less problematic. The paper develops a series of optimal strategies depending on infection rates of imports, anticipated marginal damages from infected but undetected imports, and consumer surplus.

Policy in an International Context

There have been two broad policy approaches to control NIS through trade: one focusing on vectors (usually shipping) and the other on limiting the amount of imports entering the country either by quarantine bans or tariffs, or by customs or port inspections. Both approaches must be applied within the larger context of international relations.

The United States is bound by two major trade regimes: the North American Free Trade Area (NAFTA) and the World Trade Organization (WTO). Within the WTO's legal framework, two agreements with potential bearing on AIS policies are the SPS Agreement (sanitary phytosanitary), dealing specifically with issues of human, animal, and plant health, and the TBT Agreement (technical barriers to trade), dealing with coordination of product regulations and setting criteria for imposing potentially discriminatory technical standards on imports. SPS standards are based on risk assessment, with "zero" risk considered a reasonable goal for a country to pursue. The risk assessment process under SPS standards is not inconsequential and the cost of conducting such analysis can be prohibitive (Jenkins 1996).

As compared with the WTO, NAFTA allows national governments more latitude over their technical standards and SPS measures, which could impact policy surrounding invasive species. A recent study by the Commission for Environmental Cooperation (CEC) (Perrault et al. 2003) showed that the NIS impacts from regional trade primarily exacerbate impacts of global trade. It determined that trade among NAFTA countries spreads invasive species that have been introduced as a result of trade of NAFTA countries with non-NAFTA countries. Many fewer examples exist of regional trade facilitating introduction and establishment of an invasive species within NAFTA countries. The study also purports that since NAFTA was enacted, regional and global trade have grown significantly, while the capacity to inspect for NIS has remained constant.[6] As a result, the potential for introduction of NIS via trade has increased significantly. Another study for the CEC by Murray, Fernandez, and Zertuche-Gonzalez (2005) addresses impacts of invasive seaweeds within the NAFTA Pacific region in the context of aquatic trade vectors of shipping, aquarium trade, and aquaculture.

General Cost Studies and Issues of Aggregation

There are two studies that attempted to estimate the national cost of invasive species, both terrestrial and aquatic, in the United States. The first is "Harmful Non-Indigenous Species in the United States" by the Office of Technology Assessment (OTA) of the U.S. Congress (OTA 1993). It details both the ecological impacts and estimated economic impacts of those invasive species considered harmful, rather than all invasive species inhabiting the country. The report estimated the total cost of damages related to 79 harmful species to be in the range of $131 billion to $185 billion total for the period 1906–1991. For aquatic invasives, OTA considered 111 species of fish (88 percent of total known invasives) and 88 mollusks (97 percent). Of those considered, 4 fish species and 15 mollusk species had high negative impacts. OTA estimated that the cumulative loss to the United States for three harmful fish species was $631 million, and $1,630 million for three aquatic invertebrates. OTA reports that spending

[6] Approximately 2 percent of goods are inspected. Thus, if the volume over which this percentage is applied is increasing, the total number of introductions may be increasing as well.

on control of aquatic plants in the United States is $135 million per year.

Pimentel et al. (2000) and Pimentel, Zuniga, and Morrison (2005) produced a more recent study, attempting to update and expand these cost estimates. At the time of the study, OTA estimated that there were 4,500 harmful species in the United States. Pimentel et al. (2000) estimated 5,000, and by 2004 that estimate had increased to over 6,000 (Burnham 2004). Examining a series of case studies, Pimentel et al. (2000) estimate that the total economic damages and associated control costs for the United States due to "harmful non-indigenous species" is $147 billion annually and revised to $128 billion annually according to the 2005 study.[7] They attribute their higher estimate (*vis-à-vis* the OTA study) to the broader base at which they looked and the increase in the economic cost estimates available for many invasive species. However, they also characterize their cost estimates as low because the study does not take into account the extensive ecosystem damage caused by these species.

The impacts estimated by Pimentel and co-authors and by OTA are anecdotal in nature and did not use systematic empirical methods of estimating costs, which would have provided a statistical basis to judge the validity of the estimates. There was also no attempt to incorporate the impacts on ecosystems services or explicit consideration of the potential benefits provided by some of these invasive species. Although the Pimentel estimates are widely cited, they are just a first step in estimating the true scale of the impacts. The OTA (1993), Pimentel et al. (2000), and Pimentel, Zuniga, and Morrison (2005) studies illustrate the difficulty in quantifying the impacts of invasive species at a national or smaller scale of aggregation.

Government spending on invasives may be a further guide in estimating costs. For fish and aquatic invertebrates, $22.5 million in federal funding was given out in 1999 [U.S. General Accounting Office (GAO) 2000]. The U.S. Geological Service's Aquatic Nuisance Species Program had a $5.7 million budget for 2001 (Sturtevant and Cangelosi 2000). The Department of Defense and Department of Commerce spent $3 million and $1.1 million respectively on zebra mussel control in 1999 (GAO 2000).

Empirical Cost and Benefits Estimates

The empirical studies on the impacts of AIS vary in terms of location and scale. We do not attempt to extrapolate or aggregate beyond the original scale even if other locations and scales share similar species and groupings. A list of selected references and estimates is provided in Table 1.[8]

Fish

Pimentel et al. (2001) and Pimental, Zuniga, and Morrison (2005) report that a total of 138 non-native fish species have been introduced into the United States, with economic losses of approximately $1 to $5.7 billion annually. A number of species-specific studies have also been done. The sea lamprey has caused great losses to the commercial and recreational fisheries of the Great Lakes as a parasite on native fish. Control methods for lampreys include lampricide for larvae control, barriers, traps, and a sterile male release program (Lupi, Hoehn, and Christie 2003). Estimates of annual control costs for affected states range from $304,000 for New York to $3.3 million for Michigan (GAO 2000) (for more lamprey estimates see NISC 2001 and Jenkins 2001).

Lupi, Hoehn, and Christie (2003) estimate the benefits of lamprey control on the St. Mary's River for Michigan anglers. A random utility model of recreational fishing for Michigan anglers who fished during the 1994–95 season was used to estimate economic benefits of increases in Lake Huron trout populations as a result of lamprey control. Benefits were measured in the year 2015 and ranged from $3.2 million annual benefits to $5.8 million. Two other sources report on the benefits of control. The Great Lakes Fishery Commission reports recreational benefits in the range of $2.1–4.3 billion per year (Sturtevant and Cangelosi 2000). Lost fishing opportunities and indirect economic impacts if control were terminated are estimated at $675 million annually (OTA 1993).

[7] We used the year of the original study (2000) to index both these estimates. Individual estimates within these totals were not indexed in either of the aggregate estimates by Pimental et al. (2000) and Pimental, Zuniga, and Morrison (2005).

[8] For brevity, we do not include all estimates from the references in Table 1. Readers should check the original reference for a more complete listing of estimates and species covered.

The ruffe is another fish that has invaded the Great Lakes. Control includes toxins, trawling, and ballast water management. Hushak (1997) estimated losses of $724 million for the sport fishery in Lake Erie between 1985 and 1995. Leigh (1998) evaluated the benefits and cost of a proposed 11-year ruffe control program in the Great Lakes. Total costs for the control program would be $13.6 million. The benefits of control are estimated based on the value of both commercial and sport fishery impacts over a 50-year time period. Without the control program, ruffe populations are estimated to expand to all Great Lakes and to cause declines in walleye, yellow perch, and whitefish. Assuming that benefits accrue over a 50-year time period, the net present value of benefits varied between $119 million and $1 billion.

Settle and Shogren (2002) model the interaction between native cutthroat trout and the introduced predatory lake trout in Yellowstone Lake in Yellowstone National Park. They develop a bioeconomic model of the lake's ecosystem which provides a comparison of optimal policy action with current policies for removing lake trout and determine that an optimal lake trout control program could be created for $173,000.

Crustaceans

Invasive crustaceans include the European green crab, the Chinese mitten crab, the opossum shrimp, and some species of crayfish. Lafferty and Kuris (1996) estimate the commercial fishery damage caused by European green crab along the Pacific coast. The estimated values for affected Dungeness and rock crabs, mussels, oysters, and bait in northern and central California coast is $22.8 million annually. If southern California were to also become affected, then $4.9 million would be added to the estimate. In addition, if Puget Sound were impacted by European green crab, an increase of $59 million would be made to the base estimate (Lafferty and Kuris 1996).

Mollusks

Pimentel et al. (2001) report that 88 species of mollusks have become established in the United States with economic costs of $1.7 billion annually. Zebra mussels are one of the most studied and well-known aquatic invasive species. Zebra mussels colonize docks, locks, ship hulls, water intake pipes, and other mollusks, and cause great damage to power plants and water treatment facilities. Controls include biocides, chlorine, thermal treatment, and mechanical/manual removal (Jenkins 2001). There are many estimated costs for zebra mussels but the estimates are not always reported in the same units nor do they measure the same impacts, which makes aggregation difficult. O'Neill (1997) reports on a 1995 study of 35 states and three Canadian provinces that found the economic impact of zebra mussels to have total costs of $83 million annually. A number of sources report the general costs of the mussel to be around $6.5 billion for a 10-year period (1990–2000) in the Great Lakes (Sun 1994). However, another estimate puts the cost of damages over 10 years to intake pipes, water filtration equipment, and power plants at $3.2 billion (Cataldo 2001). Many of the cost estimates deal with the impacts on power plants and water treatment plants. Costs to power plants range from $6,700 per hour for a 200-megawatt system to $127 million annually for U.S. Great Lakes power plants (OTA 1993, Armour, Tsou, and Wiancko 1993). For Great Lakes water users with lake water intake structures, Park and Hushak (1999) report that total monitoring and control costs were $149 million from 1989 to 1994, and averaged $37 million annually from 1992 to 1994. Costs for water users in the Great Lakes range from $318 per facility in 1994 and $3.3 billion annually (Armour, Tsou, and Wiancko 1993, Jenkins 2001; also see Hushak, Deng, and Bielen 1995a and 1995b, Reutter 1997, and Sturtevant and Cangelosi 2000).

A few studies related to the impact of zebra mussels on recreational activities have been done. Vilaplana and Hushak (1994) conducted a survey of Ohio residents to determine the effects at Lake Erie. Boat owners reported expenses for protective paints (average annual cost per owner was $130), additional maintenance ($240), and insurance costs ($290) related to the mussel, but the sample size was small (13 percent). Sun (1994) conducted a similar study on Lake Erie recreation using a travel cost model, but results were contradictory, in that both positive and negative impacts were found.

Estimates for the Asian clam include $10 million in compliance costs in 1980 for the nuclear electric industry, and $2.2 billion annually in the early 1980s in terms of total losses (OTA 1993). Cost-effective control strategies for oyster drills at different life stages were investigated by Buhle, Margolis, and Ruesink (2004).

Other Invertebrates

Invasive nemertean worm species destroy commercially valuable red crab species in the Pacific Northwest (Kuris and Lafferty 1992). Fernandez (2006a) estimates the economic value of red crabs in Canada and the United States according to preventative and reactive invasive species abatement using data from the Pacific Coast Fisheries Information Network (PACFIN). *Bugula neritina* is an invasive bryozoan, but has pharmaceutical value as Bryostatin, an anti-cancer substance (Marsa 2002). This pharmaceutical use is a benefit that should be weighed against any economic costs.

Plants

Aquatic or riparian invasive plant species include hydrilla, European loosestrife, Eurasian water milfoil, melaluca, and salt cedar. Hydrilla blocks irrigation canals, enhances sedimentation in flood control reservoirs, interferes with water supplies, impedes navigation, and reduces the productivity of native fisheries. Similar impacts occur from water milfoil (Jenkins 2001). Florida spends approximately $21 million annually on hydrilla eradication and control for 85,000 acres of affected waters (OTA 1993, Rockwell 2003). In a study of hydrilla on a Florida lake, Bell and Bonn (2004) estimate that recreational values at risk from hydrilla were $857,000 annually. European loosestrife invades wetlands and endangers native plants and wildlife by changing the resident plant community and altering the structure and function of the wetland (Jenkins 2001). It is estimated that European loosestrife imposes $48 million a year in control costs and forage losses (Pimentel et al. 2000). Zavaleta (1999) estimates damages including water supply through replacement cost, flood damage through avoided damage, and wildlife values of crane, eagle, and bighorn sheep through benefits transfer from an invasive shrub, tamarisk, at $137 to $370 million annually.

Rockwell (2003) summarized the literature on the economic impact of aquatic invasive weeds. Relatively few estimates of the harm done by aquatic weeds or the benefits of control are available from the literature. Recreational benefits are the primary form of benefits estimated for weed control. Rockwell uses benefit-cost ratios from the literature to generate an estimate of the national impacts of aquatic weeds, ranging between $1 and $10 billion annually.

Seaweed, Algae

A study that relates coastal property to green algae (seaweed) impacts is by Cesar, Vanbeukerling, and Prince (2002). The authors' estimates show that algal blooms on the Kihei coast of Maui, distributed over a 16.1 km length of study area, resulted in $21.8 million in potential revenue loss annually. This total can be disaggregated into $9.8 million from reduced property values and $11.2 million from reduced occupancy rates at hotels. Additionally, $1.9 million in tax loss occurs. Note, these figures are listed in the study under the category of coastal property for abatement benefits because the revenues would not be lost if abatement were to succeed in stopping the impacts of the algal blooms.

Nunes and van den Bergh (2004) empirically estimate through travel cost and contingent valuation the value that Dutch residents place on ballast water abatement in the Rotterdam port and on coastal water quality monitoring of algae. The analysis includes nonmarket values of recreation, health, and marine ecological impacts. The authors derive the existence value by process of elimination of other categories of values, and this calls into question the validity of that monetary estimate.

Government expenditures on early response removal of *Caleurpa taxifolia* in two harbors in southern California for 2000 and 2001 were $4.3 million over two years (Padilla and Williams 2004).

Conclusion

This paper reviews the economic literature on aquatic invasive species, focusing on policy options, empirical measures, and challenging theoretical issues. The most obvious conclusion of the paper is that the literature is still in its infancy. Current empirical estimates are not comprehensive enough to determine the national or regional economic impacts of aquatic invasives. Additionally, the realm of impact categories differs across the scale of analysis and method of estimation. By and large, there are few estimates of the nonmarket impacts using known methods. We have discussed here mostly the ones that measure impacts on recreation, rather than those related to more intangible ecosystem attributes. A systematic approach is needed to more clearly and comprehensively account for different scales and more categories of impacts, as well as to consistently utilize similar methods of estimation.

The unique circumstances surrounding aquatic invasive species add a level of complexity to the task that increases difficulties involved in such valuations at a geometric rate. Some studies have adopted the logic of biologists to focus on pathways rather than species when attempting to quantify abatement costs and values of damages. Any attempts to aggregate to the U.S. national level to characterize impacts at that scale may focus on the volumes of such pathways nationwide. Besides the common measurement problems and lack of observable data, measuring the economic costs of aquatic invasive species involves determining rates of biological propagation which do not always conform neatly with economic metrics due to spatial and temporal scale variations. There are also the difficulties associated with assessing the risks of invasives, but some theoretical studies we have reviewed demonstrate ways to make prevention and control decisions under risk. Clearly, it will be challenging to apply these tenets in an empirical study that generates actual dollar values of impacts. Some of these theoretical studies address specific policy options, such as subsidies for ballast water treatment. Further research should extend these to empirically estimate the impacts of these proposed programs in order to get a more comprehensive understanding of the true levels of monetary impacts.

These issues combine to make policy options difficult to both formulate and evaluate, especially *a priori*. As the literature points out, invasive species and their control have definite public good aspects and thus call for some level of government intervention. However, to what extent and what form that intervention takes place depends on a myriad of issues associated with the region, the ecosystem, and the species involved. Optimal policy appears to be as unique as the individual species or ecosystem it is attempting to control and protect. However, this literature review has provided a look at the range of impacts as well as some general comparisons of prevention and control (eradication) strategies. Biologists assert that preventative measures are the best to control the spread of unintentional aquatic invasive species (Ruiz and Carlton 2003). More economic analysis is needed to expand the limited studies surveyed here in determining whether prevention is most cost-effective compared to other forms of control (early response, eradication, etc.) at different scales.

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