Final Report

Title of Project: Economic impact of ballast-mediated invasive species in the Great Lakes

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Abstract

A question of critical importance for policy discussions about oceanic shipping into the Great Lakes is "when benefits *and* costs of shipping (as it has been practiced) are considered, does oceanic shipping into the Great Lakes provide a net benefit or net cost for the Great Lakes region?" Or to put it another way, "What would it be worth investing in ballast water management improvements?" Our project seeks to address part of the answer to these questions—the costs of invasive species that have been introduced via ballast discharges. We worked to estimate the net costs of the species that have been introduced into the Great Lakes via ballast releases since the opening of the Saint Lawrence Seaway in 1959. Under this overall goal are five specific objectives: 1) Determine the ecological changes caused by nonindigenous species that were introduced and established in the Great Lakes via ship ballast discharges; 2) Quantify the minimum net financial cost (based on market costs) imposed on the Great Lakes region by shipping-mediated nonindigenous species; 3) For a subset of high risk species, forecast their potential range in North America; 4) Assess how unquantified costs might change our evaluation of the net cost of the species and net value of shipping (by unquantified costs, we mean market costs imposed outside the Great Lakes region and non-market costs imposed within and outside the Great Lakes region); and 5) Develop policy recommendations and an outreach strategy to inform the public and policy-makers as decisions are made about the management of ballast and the St. Lawrence Seaway. We used literature review and structured expert judgment to determine percent impacts of ship-borne nonindigenous species on a variety of ecosystem services including commercial and sport fishing, wildlife viewing, and raw water usage. We translated these percent impacts into conservative estimates of economic impacts using economic models. We found that at least $200 million of economic benefits were lost because of ship-borne invasive species in 2006. This finding is the best, most comprehensive estimate of the impacts of ship-borne invasive species in the Great Lakes. In pursuing our research goals, we employed a novel approach for assessing impacts of alien species. To communicate our important research results, P.I. Lodge testified before the U.S. House Committee on Transportation and Infrastructure, and Lodge, economist collaborator Finnoff, and graduate student Rothlisberger held a press conference that was timed such that our findings could be considered in policy deliberations at the federal level.

Introduction

The St. Lawrence Seaway, opened in 1959, allows international shipping vessels to enter all the Laurentian Great Lakes. As a set of international ports, the Great Lakes are a beachhead for the introduction of aquatic nonindigenous species (NIS). Eighty-four NIS have become established in the Great Lakes since 1959. Vectors associated with human navigation, primarily the release of ballast water, are responsible for introducing 57, or nearly 70%, of these species (Ricciardi 2006). These species introductions have coincided with numerous environmental changes in the Great Lakes. Some of these changes are directly attributable to NIS. Such impacts include beach fouling by zebra mussel shells and the decline of the yellow perch fishery linked with the presence of round gobies in southern Lake Michigan (Table 1).

In this project we sought to estimate their ecological and financial impacts of these 57 ship-borne species on the Great Lakes ecosystem and its regional economy. Of these NIS, many have few or no known impacts (Table 1). Some, however, such as the zebra mussel, have had enormous ecological and economic impacts. Even for a species like the zebra mussel, which has been studied extensively, broad-scale impact assessment is not straightforward. Assessing impacts of even less well-studied species is much more difficult, especially because there may be synergistic interactions among multiple NIS that modify the respective impacts of each. To obtain impact estimates, we are used two complimentary techniques: literature review and expert elicitation (supported partly by additional funding from US EPA). These impact estimates describe the extent to which NIS have altered ecological conditions in the Great Lakes and inform damage parameters in the computable general equilibrium economic model that we used to ascertain regional financial losses.

Narrative Report

The major goals and objectives of this SeaGrant funded project were:

1) To determine the ecological changes caused by nonindigenous species that were introduced and established in the Great Lakes via ship ballast discharges;

2) To quantify the minimum net financial cost (based on market costs) imposed on the Great Lakes region by shipping-mediated nonindigenous species;

3) To forecast the potential range in North America for a subset of high risk species;

4) To assess how unquantified costs (for currently unstudied species, for market costs imposed outside the Great Lakes region, for non-market costs imposed within and outside the Great Lakes region) might change our evaluation of the net cost of the species and net value of shipping; and

5) To develop policy recommendations and an outreach strategy to inform the public and policy-makers as decisions are made about the management of ballast and the St. Lawrence Seaway.

To achieve Goals 1 and 2 we needed to deviate from our original plan (i.e., literature review only) for gathering the data needed to quantify ecological changes and financial costs caused by NIS. This change in plans required additional funding (procured from EPA as an explicit add-on to this project) and coordination with consultants that slowed our progress, but allowed us to combine the literature review with

a powerful research technique, structured expert judgment, in a novel way to address our questions.

<u>Goal 1:</u> To determine the ecological changes caused by nonindigenous species that were introduced and established in the Great Lakes via ship ballast discharges.

Literature review:

We completed a thorough review of the scientific literature on the ecological and economic impacts of all 23 (out of 57) ship-borne NIS for which we could find published information. During the summer of 2005, graduate student John Rothlisberger and a summer research assistant used the scientific and common names of our NIS as keywords to search databases of peer-reviewed publications, gray literature (e.g., government agency reports), and books. We read and annotated all sources, noting any mention of ecological or economic impacts (Table 1). The citations for these sources and our detailed notes on them have been entered into a searchable electronic database.

From the literature review we obtained a large volume of important information about the biological and ecological details of some of the NIS. The species that had been well studied were those that have had, or are likely to have, substantial economic impacts. For these species, information on the types of economic impacts they may have was also available in the literature. On the other hand, an important finding was that for more than 80% of the species, very little or no relevant information exists (Table 1). Furthermore, with the possible exception of the zebra mussel, there is little or no corroborated published data on the broad-scale impacts of these species on the ecosystems and economies of the Great Lakes region. What information does exist arises mainly from small-scale research into ecological impacts. Thus, there is much uncertainty regarding region-wide environmental and financial impacts.

The implementation of the Computable General Equilibrium regional economic models to study the effects of shipping-mediated NIS on the entire economy requires us to obtain estimates of the damages to each economic sector (e.g., commercial fishing, power generation, navigation) that are attributable to NIS. To obtain this information, we required a method that would allow us to separate the effects of stressors such as overfishing, pollution, and hydrological alterations from those of shipping-mediated NIS. While the literature review was invaluable in determining the types of impacts that are and could be attributable to NIS, it did not produce the type of information needed to estimate damages linked with NIS at the regional scale. Structured expert judgment is a way to gain scientifically credible information from such a knowledge base and to simultaneously gauge the degree of uncertainty associated with estimates of NIS impact levels (Cooke 1991).

We received additional funding from EPA to conduct a structured expert judgment panel in the fall of 2007. This is enabling us to accomplish the original goals of the project more robustly than if we had relied on the literature alone, as we detail in the next section.

Structured expert judgment:

Structured expert judgment, also known as expert elicitation, has been used many times in other fields to estimate impacts and system-wide responses to environmental

stressors (Burgman 2005, Cooke and Goosens 2008). Employing it to estimate NIS impacts is, however, highly innovative. As is the case on this project, expert elicitation is used when two conditions are met: (1) There is substantial scientific uncertainty about a process and/or the consequences of a process about which policy decisions are required; and (2) Empirical observations of the process or its consequences are theoretically possible, but are, for some reason, unfeasible (Cooke and Goosens 2008). Possible reasons that prevent observation include spatial, temporal, financial, or ethical constraints. In our case, our inability to go back in time to prevent the establishment of oceanic shipping-mediated NIS in the Great Lakes makes it impossible for us to observe what the ecosystem would have been like now and how that would have interacted with the regional economy through time. The lack of multiple sets of Great Lakes would also preclude replication, an important component of empirical experiments. Nuclear regulatory groups, for example, face similar constraints when seeking to develop science-based policy governing safety practices at nuclear power plants. Ethical considerations preclude the release radioactive materials into the environment that would allow for empirical observations on the consequences of various types and levels of nuclear reactor accidents. Scientists do, nonetheless, study relevant processes and consequences in the laboratory and in the field (using surrogate particles), such that they become experts on what would happen if radioactive material were released into the environment. Structured expert judgment protocols have been developed to obtain expert knowledge in a scientifically valid manner, so that it can be used to inform policy (Cooke and Goosens 2000).

Analogously, scientists, managers, and industry representatives are aware of and study the effects of NIS in the Great Lakes at relatively small scales and narrow scope. Such constraints are necessary to make much of their work scientifically tractable. The valuable fruits of this work are what we found during our literature review, but this type of small-scale, species-specific information is not sufficient to generate the ecosystem- and region-wide damage estimates needed for cost-benefit analyses of transoceanic shipping in the Great Lakes. Therefore, we turned to structured expert judgment to surmount the shortcomings of the published literature in this regard.

Our budget for this project did not include the funding needed to perform a structured expert judgment procedure. We were able, however, to obtain outside funding from the US EPA to pay for expert elicitation. Securing this additional funding took time and required us to push back our project timeline. Many of our goals for this project are contingent upon obtaining valid NIS damage estimates, and therefore work on toward these goals had to wait until Spring 2008 when we completed the elicitation and associated data analysis. One of the primary expenses of the elicitation was the hiring of a consultant to help us with this research approach. We were fortunate to contract the services of Dr. Roger M. Cooke of Resources for the Future and the University of Delft, Netherlands to assist us. Dr. Cooke is one of the world's foremost researchers in the use of structured expert judgment for risk assessment and uncertainty analysis.

Our research team held several conference calls with Cooke to explain our project to him and to get his input on how we should proceed. Cooke visited the campus of the University of Notre Dame in March 2007 to become more familiar with our research and to offer additional guidance in preparation for the elicitation. In May 2007, Cooke hosted graduate student John Rothlisberger at Resources for the Future in Washington, D.C. for

three full days to write the elicitation protocol. The elicitation of expert judgments can be viewed as an instrument for making scientific measurements and as such the statistical accuracy of individual experts can be assessed if the elicitation protocol is (1) transparent to peer review, (2) does not prejudge experts, (3) encourages experts to express their true beliefs, and (4) allows for empirical quality control of results (Cooke 1991). We sought to meet all 4 of these criteria. The complete protocol is attached to this report.

We interviewed 10 experts in Fall 2007 to collect our elicitation data (names of experts listed in Table 2). Experts included fisheries biologists, food web ecologists, environmental economists and natural resource managers. All experts, of course, had specific knowledge of the Great Lakes. We used information from our literature review to prepare a briefing book that was given to the experts prior to the elicitation. We encouraged experts to review the booklet prior to their interview and to refer to it as desired during the interview. Along with the booklet, we also provided a complete copy of the elicitation protocol to the experts well in advance of their interview.

One to three members of our research team, including Rothlisberger, Dr. Cooke, and Dr. Lodge, conducted expert interviews. Each interview began with a brief presentation from the elicitors on the quantification of uncertainty via expert judgment and related issues. The expert also responded to several practice questions, similar to those on the questionnaire, for which they received immediate feedback as to the true value of the variable they were assessing. Interviews followed a standard script and generated quantitative estimates of impact levels and uncertainty about those levels.

During the elicitation, experts were asked to provide the 5^{th}, 50^{th}, and 95^{th} percentiles of their subjective cumulative probability density function to quantify their knowledge and uncertainty regarding the impacts of ship-borne NIS on several important ecosystem services in each of the Great Lakes. To explain the meaning of these percentiles the following example is given.

How many total pounds of lake trout were caught in 2005 in Lake Superior by commercial fishing? 5% _____ 50% _____ 95% _____

Presumably, this number is uncertain. If the expert fills in

How many total pounds of lake trout were caught in 2005 in Lake Superior by commercial fishing? 5% ___50,000 50% __90,000_ 95% _140,000_

this means that she believes there is a 5% chance that the actual number is below 50,000; there is a 50-50 chance that it is below 90,000, and a 95% chance that it is below 140,000.

The true value is **80,703lbs**. This is not a surprising value relative to this assessment. If the value were 30,000 this *would* be surprising, as would 150,000. In each of the latter cases, the realization would be outside the 90% confidence band.

An expert's probabilistic assessments are *statistically accurate* if 10% of the realizations should fall outside the 90% confidence band; 50% of the realizations should fall on either side of the median (50% value).
If the expert's assessments had been

5% __2,000___ 50% ___200,000__ 95% __500,000__

She would have been equally un-surprised, but her assessments would be *less informative*.

A good probability assessor is one whose assessments show both good *statistical accuracy* and are *informative*. Of these two, statistical accuracy is more important; informativeness is important to discriminate between statistically accurate assessments.

It is essential for the credibility of the results that the combined expert judgments display good statistical accuracy and high informativeness. For this reason, during the elicitation we asked experts to assess items whose true values were not known at the time of the interview, but which became known within the time frame of the study (referred to as calibration variables). This allowed us to measure how well calibrated each expert was with respect to statistical accuracy and informativeness. Using this calibration information we weighted each expert's assessments accordingly to obtain a single combined median estimate, with uncertainty bounds, of the percent impacts of ship-borne NIS in the Great Lakes. The elicitation includes questions about the effects of ship-borne NIS on four ecosystem services: (1) commercial fishing (as in the above example), (2) recreational angling, (3) wildlife viewing/eco-tourism, and (4) raw water usage. For each of these ecosystem services, we asked each expert to give a median estimate and an uncertainty distribution of what the variable's value was in 2006 and what it will be in 2025, and what it would have been in 2006 and 2025 if not for oceanic shipping-mediated NIS in the GL.

We reviewed and analyzed the experts' answers and report them as individual expert assessments and combined assessments for each variable (Figures 1, 2). We combined expert assessments in two ways: (1) each expert's assessment was given equal weight and (2) individual assessments were weighted according to the expert's performance (both accuracy and informativeness) on the calibration variables. The technical details of both combination methods are described in Tuomisto et al. (2008).

We calculated median estimated impacts and the associated 5th and 95th percentile confidence bounds using the convolution of the joint probabilities of the without NIS and with NIS performance-based combination (PBC) distributions for 2006 and 2025, assuming independence of all variables. This produced a distribution of differences between each without NIS-with NIS pair of variables. We then divided the 5th, 50th, and 95th percentiles of this distribution of differences by the appropriate 2006 or 2025 median PBC assessment and multiplied each by 100 (Table 3). We also recorded the additional costs to raw water users in the Great Lakes region that experts assessed were attributable or would be attributable to biofouling in 2006 and 2025, respectively (Table 4). For brevity in this narrative, we focus on results pertaining to impacts in 2006.

Results from our survey of experts suggest that if ship-borne species had not been introduced into the Great Lakes, the Great Lakes would be providing society with substantially higher harvests in the commercial fishery and more participation in the

recreational fishery, with median damage estimates for 2006 ranging from 13-33% in the commercial fishery and 11-35% in the recreational fishery, depending on which lake one considers (Table 3). The indicated 35% percent decrease in the Lake Superior recreational fishery needs some further explanation, however, as it is generally accepted that ship-borne species have caused the least disruption on Lake Superior. We couldn't get solid calibration data for 2006 participation in the recreational fishery in L. Superior. This lack of calibration data kept us from combining experts' opinions according to their performance for this variable. Also, there were large discrepancies among experts as to median impacts here, with several indicating no impact from ship-borne species, but with others estimating impacts at 70 to 150%. Because of these circumstances specific to Lake Superior, we view the high percent impact on participation in the Lake Superior recreational fishery with the most skepticism of any of our findings.

The experts also estimated that the ability of the Great Lakes region to sustain wildlife watching – including various ecotourism-related activities – is about 1% lower than it would have been without ship-borne species.

There was a wide range of costs to raw water users, averaging $30K/facility/year at most types of facilities, such as municipal water plants and fossil fuel power plants. Experts expected costs at nuclear power plants were much higher, nearly $120K/facility/year.

<u>Goal 2:</u> To quantify the minimum net financial cost (based on market costs) imposed on the Great Lakes region by shipping-mediated nonindigenous species.

Drs. Jay Shogren and David Finnoff, the economists on the project, prepared a Computable General Equilibrium (CGE) economic model for the Great Lakes region, including Ontario (which may need to be handled as a separate model). They are now in the final stages of incorporating the damage estimates from the expert elicitation to determine the region-wide financial losses arising from shipping-mediated NIS. Our project team purchased IMPLAN data for the Great Lakes states and Ontario to parameterize these CGE models. Our estimates will be the only estimates of regional economic impacts, and will be valuable to inform cost-benefit analyses of measures to restrict the introduction of additional NIS into the Great Lakes (e.g., on-board ballast water treatment). Highlighting the success of the CGE method we will use, Shogren and Finnoff are in the final stages of friendly review on a manuscript that employs the same method to assess the potential economic impact of a zebra mussel invasion in the Columbia River basin (Finnoff et al. *in review*).

As a preliminary step, we used a less sophisticated approach than a CGE to estimate changes in consumer surplus (one component of economic damages) attributable to the presence of ship-borne NIS. This more simple approach relied on linear market models. These models provide what we expect will be conservative estimates of economic impacts and will be useful benchmarks in our analysis of the more complicated CGEs. More specifically, to translate percent impacts on ecosystem services into economic values, we used simple linear market models for each ecosystem service. In general, the demand curve in a market model represents each buyer's maximum willingness to pay – arranged from highest to lowest – at each supply quantity of the good or service. On the other hand, the supply curve reflects each seller's minimum willingness to accept, arranged from lowest to highest. The equilibrium of these models,

which gives the market price and quantity, is found at the intersection of demand and supply.

When supply equals demand at a market-clearing price, both consumers and producers benefit from the exchange. If anything restricts this ability to trade, including changes in ecosystem services due to invasive species, benefits to society from exchange can be lost, as measured here by changes in consumer surplus. These losses represent an opportunity cost to society (McIntosh et al. *in press*). Our first step in using this kind of model to calculate changes in consumer surplus associated with ship-borne NIS was to find the actual consumer surplus associated with a given ecosystem service in 2006. We then shifted the supply curve to correspond with hypothetical increases in ecosystem services in the absence of ship-borne species, as determined from the median of the combined expert assessment (Tables 3, 4), and calculated what would have been the consumer surplus. Subtracting the 'with ship-borne species' consumer surplus from the 'without ship-borne species' consumer surplus gave the loss in consumer surplus attributable to ship-borne species.

Because the U.S. sport fishery is much larger than the U.S. commercial fishery, our economic models suggest that a conservative estimate of these losses was about $124 million for the sport fishery and $2 million for the commercial fishery in 2006 (consumer surplus in Table 5 for own-price demand elasticity = -1.5). Given that wildlife viewing is such a large (and growing) industry, our economic models suggest that even a conservative estimate of this impact is quite large, about $47 million for 2006 (consumer surplus in Table 5 for own-price demand elasticity = -1.5). Experts indicated that the increased costs for raw water users totaled about $27 million for 2006 (Table 4). Adding up all impacts, our initial estimate for changes in consumer surplus due to lost ecosystem goods and services plus additional costs from biofouling comes to about $200 million for 2006.

The $200 million estimate of losses in 2006 is at the low end of our plausible range of estimates because it results from using the most conservative parameter value for own-price demand elasticity. While estimated economic losses rise with less conservative values for this parameter (i.e., -0.15 and –0.5), it is not yet possible to anticipate what intermediate or maximum estimates of impact may emerge from more complete analyses. It is also important to note that our estimates do not yet consider ecosystem goods and services in Canada, but the same four economic sectors with which we dealt also exist there and we are working to include Canada in our more sophisticated economic models. Finally, our analysis does not include damage outside the Great Lakes region (e.g., damages from dreissenid mussels in the western U.S.), although these damages too are attributable to shipping in the Great Lakes.

Our consideration of the effects of ship-borne species on Great Lakes sport fishing and wildlife watching are important advances given the economic importance of these activities to the region. Most previous research has been concentrated on Great Lakes raw water users, but it appears likely that recreational ecosystem services have been significantly impacted by invasions and indeed provide the bulk of the impacts we find.

It is important to remember these results are still preliminary. Each of our estimates is calculated in isolation of the other and presumes that everything else imaginable such as environmental and economic conditions would have remained exactly

the same with and without the invaders. A more complete analysis would include producer surplus and interactions among different economic sectors. We intend to incorporate these aspects and refine our models and findings as we complete this research goal with the Computable General Equilibrium model.

Goal 3: To forecast the potential range in North America for a subset of high-risk species.

Under this goal we predicted the potential spread of selected high-risk species, which required predictions of both dispersal and potential habitats. Regarding dispersal, Jon Bossenbroek, led us in a publication on a related Sea Grant project that predicted, on the basis of recreational boater movements, that the Columbia and Colorado River basins have a higher risk of invasion by zebra mussels transported by recreational boaters than other areas west of the 100th meridian (Bossenbroek et al. 2007). This research was in press before zebra mussels were discovered in Lake Mead, within the Colorado's basin.

Under the combined auspices of this and other projects, we have published national environmental niche models for zebra mussel (Drake and Bossenbroek 2004), several fish species (Drake and Lodge 2006a, b), and Chinese mitten crab (Herborg et al. 2007). These models of potential geographic distribution show that many uninvaded locations in the US are probably suitable for zebra mussel colonization, invasive fishes, and Chinese mitten crab. Perhaps the most surprising result is that many of the Great Lakes are susceptible to invasion by the migratory Chinese mitten crab. Though it is not yet known to be established in the Great Lakes, live adult Chinese mitten crabs have been discovered in lakes Erie and Superior (http://www.qc.ec.gc.ca/csl/inf/inf003_007_e.html). During the literature review, a potential range map for New Zealand mudsnail (*Potamopyrgus antipodarum*) in North America was produced with an Australian collaboratory (www.ecolsoc.org.au/Conference/ESA2005/documents/SarinaLoo.pdf).

Our success with these project goals has encouraged us in plans to produce additional (and better) potential range maps for more species. Toward this end, we acquired water quality and lake sediment data to develop niche models for the Great Lakes, and are gathering data for other regions. These data include water quality data from the GLENDA database (USEPA), and sediment data from NWRI Canada. As sufficient data are acquired, we hope to produce potential geographic distribution models for a number of other NIS in the Great Lakes, but we have not yet completed these models. During our literature review, we gleaned published species point occurrence data that will aid us in this effort. The species that are candidates for modeling are those with a high potential for ecological and economic impacts across the continent. These species include *Bythotrephes longimanus*, *Neogobius melanostomus*, *Dreissena bugensis*, *Corophium curvispinum*, *Corbicula fulminea*, *Echinogammarus ischnus*, and *Cercopagis pengoi*.

Goal 4: To assess how unquantified costs might change our evaluation of the net cost of the species and net value of shipping.

Meeting this goal awaits the final outputs from the regional economic modeling. Once we have estimates of baseline financial losses from our regional economic model, we will modify various parameters in the model to investigate scenarios involving unquantified costs.

<u>Goal 5:</u> To develop policy recommendations and an outreach strategy to inform the public and policy-makers as decisions are made about the management of ballast and the St. Lawrence Seaway.

We worked with Great Lakes United to produce communication deliverables (non-technical publications for public dissemination and promotion) during 2008. The primary deliverables in this regard were a press release and fact sheet (attached) available on the GLU website. To disseminate these materials to the press and public, GLU coordinated a press teleconference featuring principal investigators Lodge and Finnoff and graduate student Rothlisberger. More than a dozen reporters participated in this conference call, including one each from the Associated Press and Reuters. Following the release of the resulting story on the AP and Reuters wires, over 125 national and regional papers picked up on our report.

Our press release was particularly timely as it came out at a point, July 16, 2008, when the US House of Representatives had recently passed a bill to toughen ballast water treatment regulations for ships entering the Great Lakes and the Senate was in the process of considering their own version of the bill. We thought it essential to provide our estimates of the economic impacts from ship-borne NIS in the Great Lakes to legislators and policy makers at the time they were considering legislation to which our research was so relevant. We also thought it was important to provide an appropriately cautious context for our results because preliminary results presented at the 2008 IAGLR meeting had been widely reported in the press in misleading ways, despite our cautions to the journalists involved. Fortuitously, our press release came out on the same day as the release of a report commissioned by the National Academy of Sciences on the economic viability of the St. Lawrence Seaway. This timing enhanced press coverage of and public interest in our research findings.

In addition, we previously took full advantage of another outreach opportunity that came our way for free. In June 2007, a professional film crew from the American Museum of Natural History (New York City) spent two days filming and interviewing Lodge and his graduate students about the impact of invasions in the Great Lakes, with a special focus on ship-borne invasions. This resulted in a 7-minute documentary in the museum's Science Bulletin series of films. These films are available free on their web site (http://sciencebulletins.amnh.org/?src=h_nc) after an initial 6-month distribution to paid subscribers that include 40 other museums and science centers in the US and abroad. This film promises to be a very effective and widely used vehicle to educate the public on the damaging effects of ship-borne invasive species to the GL and North America, and on what could be accomplished with better management approaches. In a similar vein, we have been invited by NSF public affairs officer Lily Whiteman to produce a short story about our research on the impacts of ship-borne invaders for publication in the *Behind the Science* series on livescience.com, a popular website for the dissemination of science, technology, health, and environmental news. We anticipate that this story will appear on-line by the end of 2008.

Lodge testified on ship-borne invasions before a U.S. House subcommittee (see list of presentations) in spring 2007, drawing heavily on the research completed under the auspices of this project.

Lodge also accepted an invitation to speak on this project to the annual meeting of the Board of the Great Lakes Commission in Quebec City in October 2008.

Furthermore, as an outgrowth of this project and another funded by the Great Lakes Protection Fund, our research team has been selected to organize a symposium on the ecological and economic impacts of ship-borne invasive species at the annual meeting of the American Association for the Advancement of Science (AAAS) in Chicago, IL in 2009. The selection process for AAAS symposia is highly competitive and participation in these meetings offers a high-profile outreach opportunity.

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TABLES

Table 1. Summary of scientific literature documenting various types of ecological and economic impacts attributable to ship-borne species in the Great Lakes. Numbers in cells indicate the number of unique studies in the primary literature that document a particular impact by a particular species. This number is not necessarily a metric for the severity or importance of the impact, but represents the range of impacts attributable to ship-borne species and the level of scientific attention in their regard. Only 8 of 57 ship-borne NIS are included here because it was only for these species that we could find appreciable information on impacts.

	Losses in native biodiversity	Competition with natives	Predation on natives	Problematic food resource for natives	Habitat modification	Infrastructure fouling	Fisheries impairment	Recreational impairment	Risks to human health	Taste and odor problems in water supply
Echinogammarus ischnus		2								
Eurasian Ruffe		8	2				1			
Round Goby		4	7	6					4	
New Zealand mud snail		2								
Spiny waterflea		3	11	8				1		
Fish-hook waterflea		4	2	2			1	1		
Dreisssenid mussels	4	20	6	5	33	8	2	4	3	2

Table 2. Experts interviewed and the professional title, affiliation, and qualifications of each (listed alphabetically).

Name	Title, affiliation, and qualifications
Richard Aiken	Natural resource economist with the US Fish and Wildlife Service. His office administers and analyzes the USFWS National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (USFWS 2007).
Renata Claudi	Former employee of Ontario Power Generation whose main duties included dealing with biofouling problems, active organizer of the annual International Conference on Aquatic Invasive Species, and owner of a biofouling consulting firm.
Mark Ebener	Fisheries assessment biologist with the Chippewa-Ottawa Resource Authority. Ebener has chaired the Lake Superior and Lake Huron Technical Committees and served on the Lake Michigan Technical Committee of the Great Lakes Fishery Commission (GLFC).
Leroy Hushak	Professor Emeritus of Agricultural Economics at The Ohio State University. Hushak has conducted research on the value of recreation in the Great Lakes and the effects of dreissenid mussels on Great Lakes power plants.
Roger Knight	Lake Erie Program Administrator for the Ohio Department of Natural Resources. Knight has served on the Lake Erie Technical Committee of the GLFC.
Frank Lupi	Associate Professor of Environmental and Natural Resource Economics at Michigan State University. Lupi studies fish and wildlife demand and valuation and the economics of ecosystem services in the Great Lakes region.
Lloyd Mohr	Fisheries Assessment Team Leader for the Upper Great Lakes management unit of the Ontario Ministry of Natural Resources. Mohr has been active in the GLFC's technical committees for Lake Huron and Lake Superior.
Charles O'Neill, Jr.	Senior Extension Associate with New York Sea Grant and the director of Sea Grant's National Aquatic Nuisance Species Clearinghouse. O'Neill has led research initiatives regarding the fouling effects of dreissenid mussels on raw water users in the Great Lakes region and has served for the past four years as a member of the federal Invasive Species Advisory Committee.
Don Scavia	Professor of Natural Resources at the University of Michigan and Director of Michigan Sea Grant. Scavia oversees several large-scale research projects on drivers and conditions of Great Lakes ecosystems.
Roy A. Stein	Professor of Aquatic Ecology and Director of the Aquatic Ecology Laboratory at The Ohio State University. Stein also served as Commissioner of the GLFC from 1999-2004.

Table 3. Annual ship-borne NIS impacts on US commercial fish landings, recreational fishing effort, and wildlife watching effort for 2006 and 2025. Table values indicate percentage by which each quantity would have been greater if ship-borne NIS were not present. Thus, positive percentages mean the quantity of the variable would have been that much higher without ship-borne NIS. Negative values mean that the quantity would have been lower if there were no ship-borne NIS, indicating enhancement of the variable in the presence of ship-borne NIS. The uncertainty range gives the 5th and 95th percentiles of the distribution of differences between the with- and without-NIS PBC distributions.

		2006		2025	
Category	Lake	Median % Reduction	Uncertainty Range	Median % Reduction	Uncertainty Range
Commercial Fish Landings					
	Superior	13.4	(-69.8, 122.8)	5.5	(-100.0*, 231.3)
	Michigan	21.2	(-75.8, 153.6)	20.9	(-100.0*, 336.6)
	Huron	22.8	(-89.0, 154.6)	12.4	(-100.0*, 260.7)
	Erie	17.6	(-42.7, 73.6)	16.0	(-100.0*, 230.8)
	Ontario	32.8	(-100.0*, 620.3)	25.6	(-100.0*, 1611.1)
Sport Fishing Effort					
	Superior	35.3	(-100.0*, 315.7)	17.7	(-100.0*, 330.1)
	Michigan	11.5	(-65.8, 84.3)	13.3	(-100.0*, 145.7)
	Huron	18.2	(-100.0*, 251.8)	21.4	(-100.0*, 296.0)
	Erie	14.9	(-49.8, 70.6)	8.5	(-83.1, 98.1)
	Ontario	13.3	(-81.7, 112.2)	16.7	(-100.0*, 140.7)
Wildlife Watching Effort					
	US states bordering the GL	0.8	(-70.5, 74.2)	1.2	(-100.0*, 127.6)

* Value of variable without NIS cannot be more than 100% less than it was (2006) or will be (2025) with NIS. Therefore, for logical consistency, these positive NIS impact levels have been truncated at -100%.

Table 4. Additional annual operating costs to raw water users attributable to ship-borne NIS, reported in 2007 US dollars. Regional costs are median per facility costs from combined expert assessments multiplied by the number of each type of facility in the Great Lakes region. Ninety percent uncertainty ranges appear in parentheses.

Facility Type	Year	Median Per Facility Cost (Thousands of 2007 US$)		# of Facilities	Regional Cost (Millions of 2007 US$)	
Nuclear Power Plant	2006	118.1	(43.5, 211.3)	13[1]	1.54	(0.57, 2.75)
	2025	94.6	(28.8, 252.5)		1.23	(0.37, 3.28)
Fossil Fuel Power Plant	2006	28.1	(6.6, 53.5)	260[1]	7.31	(1.72, 13.91)
	2025	24.5	(2.4, 70.8)		6.37	(0.60, 18.41)
Municipal Water Plant	2006	32.5	(4.9, 61.3)	436[2]	14.17	(2.14, 26.73)
	2025	28.1	(3.1, 85.5)		12.25	(1.35, 37.28)
Industrial Facility	2006	30.4	(4.6, 56.7)	117[2]	3.56	(0.54, 6.63)
	2025	25.6	(2.3, 71.1)		3.00	(0.27, 8.32)
Total	2006	–	–	–	26.57	(4.96, 50.02)
	2025	–	–	–	22.85	(2.59, 67.29)

[1] Power Plants in the Great Lakes Basin, Northeast Midwest Institute Report (http://www.nemw.org/Power%20plants%20in%20the%20Great%20Lakes%20Basin.pdf, accessed: 5/6/2008)

[2] Approximated from Deng (1996) and O'Neill (1996)

Table 5. Changes in total economic surplus (i.e., producer surplus + consumer surplus) attributable to ship-borne NIS in the GL in 2006, expressed in 2007 US$, for a range of own-price demand elasticities. Negative values indicate the possibility that ship-borne NIS were economically beneficial (i.e., economic surplus would have been lower without ship-borne NIS). Units of tabled values are millions of 2007 US dollars.

		Change in										
		Consumer Surplus				Producer Surplus				Total Surplus		
Ecosystem Service												
Demand Elasticity:		-0.15	-0.5	-1.5		-0.15	-0.5	-1.5		-0.15	-0.5	-1.5
Commercial Fishing												
	L. Superior	1.37	0.41	0.14		-1.26	-0.24	0.05		0.11	0.17	0.19
	L. Michigan	8.68	2.60	0.87		-8.32	-1.67	0.23		0.36	0.93	1.10
	L. Huron	6.26	1.88	0.63		-6.05	-1.23	0.15		0.21	0.65	0.78
	L. Erie	4.85	1.46	0.49		-4.58	-0.91	0.14		0.27	0.55	0.63
	L. Ontario	0.02	0.01	0.00		-0.02	0.00	0.00		0.00	0.01	0.00
	Total	21.18	6.36	2.13		-20.23	-4.05	0.57		0.95	2.31	2.7
Sport Fishing												
	L. Superior	473.88	142.16	47.39						473.88	142.16	47.39
	L. Michigan	306.69	92.01	30.67						306.69	92.01	30.67
	L. Huron	69.34	20.80	6.93						69.34	20.80	6.93
	L. Erie	321.90	96.57	32.19						321.90	96.57	32.19
	L. Ontario	63.72	19.12	6.37						63.72	19.12	6.37
	Total	1235.53	370.66	123.55						1235.53	370.66	123.55
Wildlife Watching												
	In 8 US states bordering GL	476.59	142.98	47.66						476.59	142.98	47.66

Potential Applications or Benefits:

The economic damage numbers we focus on here are the median estimates of changes in ecosystem services estimated by experts, and the low end of financial losses to the U.S. Great Lakes economy that have been inflicted by species delivered to the lakes by ocean-going ships. The $200 million sum represents the current annual opportunity cost likely absorbed by U.S. society in 2006 as a result of the cumulative effects of almost 50 years of ocean-going vessels entering the Great Lakes.

If invasive species stopped arriving in the Great Lakes via shipping tomorrow, the costs we estimated would unfortunately continue because the species already present will likely continue to have the same, or greater, impacts as they are having today. The benefits from any new management or policy initiatives, therefore, will derive from the prevention of potential future invasions, and their potential cost to society. By pointing out that the costs of previously introduced ship-borne species are large and certain to grow in the future, and that new invaders will produce more damage, our research provides important motivation for legislators, policymakers, and other researchers to take decisive steps in curtailing the introduction of additional species via the shipping-related vectors of ballast water release and hull fouling.

Keywords: nonindigenous species, aquatic nuisance species, invasive species, economic impact assessment, exotic species, Great Lakes shipping, structured expert judgment, computable general equilibrium models, Saint Lawrence Seaway, ecological forecasting, biodiversity, ecosystem services

Lay Summary

The Great Lakes are now home to 84 aquatic non-indigenous species (NIS), most of which have been transported there in the ballast tanks of ocean-going ships. These ocean-going ships from far-away regions are able to enter the Great Lakes through the St. Lawrence Seaway, which was opened in 1959. Many of these NIS have had negative economic and ecological impacts on the Great Lakes, including impacts on both recreational and commercial fishing, and tourism, to name but a few. Conversely, Great Lakes shipping does, however, provide some economic benefit to the Great Lakes region. So a question of critical importance for policy discussions about oceanic-shipping in the Great Lakes is "what magnitude of investments in improved management of ballast water is justified by the costs from NIS delivered by shipping into the Great Lakes?" This project seeks to provide a partial answer to that question-the costs of NIS that have been introduced via ballast discharges by ocean-going ships.

To answer this question we used literature review and structured expert judgment together with economic models to quantify impacts on some ecosystem services, including impacts to commercial and sport fishing, wildlife viewing and raw water usage. Our conservative estimates found that at least $200 million of economic benefits were lost in 2006 because of ship-borne NIS. These estimates are the only estimates of regional economic impacts from NIS and will help inform policy at the regional level.

International Implications

The St. Lawrence Seaway and the Great Lakes are a bi-national resource, shared between the United States and Canada. Effective policies to prevent future invasions and to cope with current nuisance species require international cooperation. Recognizing that the costs of ship-borne invaders are substantial and that they are shared between the nations may promote

continued and even increased cooperation. The economic impacts of ship-borne invasive species in the Great Lakes that we report here are for the US only, but similar impacts to ecosystem services occur in Canada. The more thorough regional economic model on which we are working will include data from Ontario and provide results on economic impacts there.

Partnerships with other institutions/individuals initiated or continued by project

- Federal: We secured additional funding to conduct the structured expert judgment component of this project through a contract from the US EPA. This funding made the completion of this project possible.
- Regional: Lodge presented project to Great Lakes Commission.
- Local & State: N/A
- NGOs: To design and implement the structured expert judgment study we contracted with Dr. Roger Cooke of Resources for the Future. We have since collaborated with Dr. Cooke on a separate research proposal and anticipate continued research partnership with him. Great Lakes United coordinated our outreach efforts.
- International: Great Lakes Commission
- Industry/Business: N/A
- Academic Institutions: N/A
- Sea Grant Programs: N/A
- Other: N/A

Publications and Presentations

Peer-Reviewed Journals/Articles/Book Chapters – Published

Drake, J.M. and D.M. Lodge. 2006a. Forecasting potential distributions of nonindigenous species with a genetic algorithm. Fisheries 31:9-16.

Lodge, DM., D.A. Andow, P.D. Boersma, and R.V. Pouyat. 2006. Commentary: Reply to letter by B.P. Caton in response to ESA Position Paper on Invasives. Bulletin of the Ecological Society of America October pp 333-334.

Drake, J.M. and D.M. Lodge. 2006b. On the distribution and extension of rainbow smelt—reply. Fisheries 31:304-305.

Lodge, D.M., S. Williams, H. MacIsaac, K. Hayes, B. Leung, S. Reichard, R.N. Mack, P.B. Moyle, M. Smith, D.A. Andow, J.T. Carlton, and A. McMichael. 2006. Biological invasions: recommendations for U.S. policy and management (Position Paper for the Ecological Society of America). *Ecological Applications* 16:2035-2054.

Herborg L-M., C.L. Jerde, D.M. Lodge, G.M. Ruiz, and H.J. MacIsaac. 2007. Predicting invasion risk using measures of introduction effort and environmental niche models. *Ecological Applications* 17:663-674.

Bossenbroek, JM, LE Johnson, B Peters and D.M. Lodge. 2007. Westward expansion of the zebra mussel in North America: forecasting a low probability-high impact event. *Conservation Biology* 21:800-810.

Costello C, JM Drake and DM Lodge. 2007. Evaluating an invasive species policy: ballast water exchange in the Great Lakes. *Ecological Applications* 17:655-662.

Finnoff, D. C., C. Settle, and J. F. Shogren. in press. Integrating economics and biology for invasive species management. Pages 37-61 *in* R. P. Keller, D. M. Lodge, M. A. Lewis,

and J. F. Shogren, editors. Bioeconomics of Invasive Species: Integrating Ecology, Economics, Policy, and Management. Oxford University Press, New York.
Herborg, L. M., J. M. Drake, J. D. Rothlisberger, and J. M. Bossenbroek. in press. Identifying suitable habitat for invasive species using ecological niche models and the policy implications of range forecasts. Pages 93-121 *in* R. P. Keller, D. M. Lodge, M. A. Lewis, and J. F. Shogren, editors. Bioeconomics of Invasive Species: Integrating Ecology, Economics, Policy, and Management. Oxford University Press, New York.
Lodge, D. M., M. A. Lewis, J. F. Shogren, and R. P. Keller. in press. Introduction to biological invasions: biological, economic and social perspectives. Pages 1-36 *in* R. P. Keller, D. M. Lodge, M. A. Lewis, and J. F. Shogren, editors. Bioeconomics of Invasive Species: Integrating Ecology, Economics, Policy, and Management. Oxford University Press, New York.
McIntosh, C. R., D. C. Finnoff, C. Settle, and J. F. Shogren. in press. Economic valuation and invasive species. Pages 225-262 *in* R. P. Keller, D. M. Lodge, M. A. Lewis, and J. F. Shogren, editors. Bioeconomics of Invasive Species: Integrating Ecology, Economics, Policy, and Management. Oxford University Press, New York.

Peer-Reviewed Journals/Articles/Book Chapters – In Preparation

Finnoff, D.C., D.M. Lodge, J.D. Rothlisberger, and R.M. Cooke. *In preparation.* Economic impacts of ship-borne invasive species in the Great Lakes region.
Lodge, D.M. and J.D. Rothlisberger. *In preparation.* History of invasions and their management in the Laurentian Great Lakes *in* J.M. Drake and D.M. Lodge, editors. Ecology of Shipping in the Great Lakes. Springer, New York.
Rothlisberger, J.D., D.M. Lodge, R.M. Cooke, and D.C. Finnoff. *In preparation.* Future of the binational Laurentian Great Lakes fisheries: environmentally and culturally driven declines?
Rothlisberger, J.D., D.M. Lodge, R.M. Cooke, and D.C. Finnoff. *In preparation.* Ship-borne nonindigenous species diminish Great Lakes ecosystem services.

Published abstracts of presentations

Rothlisberger, J.D., D.M. Lodge, D. Finnoff, and R. Cooke. Ship-borne nonindigenous species diminish ecosystem services of the Great Lakes: a structured expert judgment study. Annual Meeting of the Ecological Society of America. Milwaukee, WI. August 7, 2008.
Rothlisberger, J.D., D.M. Lodge, D. Finnoff, and R. Cooke. Ship-borne nonindigenous species diminish ecosystem services of the Great Lakes: a structured expert judgment study. International Association for Great Lakes Research Annual Conference. Peterborough, Ontario. May 21, 2008.
Rothlisberger, J.D., D.M. Lodge, J.M. Bossenbroek, et al. Ecological and economic impacts on the Great Lakes and the U.S. by shipping-mediated nonindigenous species (NIS) in the Great Lakes. Annual Meeting of the International Association of Great Lakes Research. State College, PA. May 31, 2007.

Other presentations related to this project

Rothlisberger, J.D. and R.M. Cooke, D.M. Lodge, and D. Finnoff. A structured expert judgment study on the effects of ship-borne nonindigenous species on Great Lakes' ecosystem services. Invited seminar at Resources for the Future. Washington, D.C. May 29, 2008.

Lodge, U. Minnesota IGERT presentation, 3/2008

Lodge, DOW/OSU Research Review, 2/2008

Lodge, U.S House Committee on Transportation and Infrastructure, Subcommittee on Water Resources and Environment, hearing on The Impact of Aquatic Invasive Species in the Great Lakes, 3/2007, http://transportation.house.gov/hearings/hearingdetail.aspx?NewsID=75

Lodge, National University of Singapore, Dept of Biological Sciences, 6/07;

Lodge, keynote speaker, Florida Pest Plant Council, 5/07;

Lodge, keynote speaker, Michigan State University Dept of Fisheries and Wildlife Graduate Student Researrch Symposium, 2/07;

Lodge, plenary speaker, Ecological Society of America meeting on Trade and Invasive Species, Mexico, 1/06;

Lodge, Mote Marine Laboratory, 4/07;

Lodge, Law and Environment series speaker, University of Notre Dame Law School, 2/07;

Lodge, The Nature Conservancy Freshwater Initiative meeting, Boulder (invited presentation), 1/07;

Lodge, Speaker, Environmental Forum, Stanford University, 12/06;

Lodge, The Nature Conservancy Science and Conservation meeting, Tucson (2 invited presentations), 11/06;

Lodge, organized (with co-organizers Mark Lewis, Jay Shogren) symposium at 2007 ESA meeting, "Ecological and economic theory in analyzing risk in biological invasions;"

Lodge, Indiana-Michigan St. Joseph River Basin Symposium, 6/07;

Lodge, The Nature Conservancy workshop on management of invasive species, 3/07;

Lodge, Ecological Society of America's press briefing (National Press Club) on Position Paper on invasive species, 3/06

Videos/CDs/DVDs

Invasive Species Science Bulletin. November 2007. American Museum of Natural History (New York City) (http://sciencebulletins.amnh.org/?src=h_nc)

Press Releases

Lodge, D.M. and D.C. Finnoff (July 16, 2008). "Great Lakes region losing $200 million a year to invasive species". Press release and fact sheet facilitated by Great Lakes United. Available on-line: http://www.glu.org/english/invasive_species/economy/index.htm

Buckley, C. (August 6, 2008). "Evaluating ecosystem services: a new approach to environmental protection". Press release featuring this project by the Ecological Society of America.

Undergraduate/Graduate Students

This project supported graduate student John Rothlisberger, a doctoral student currently beginning his 5th year.

Related Projects

NOAA National Sea Grant. $340,000 for 1 June 2003-31 May 2005. P.I., with the following Co-PIs or senior collaborators: Brian Leung (U Notre Dame), Jason Shogren (U. Wyoming), and David Finoff (U. Central Florida). Evaluating the ecological and economic value of the 100th Meridian Initiative.

US Fish & Wildlife Service. $40,000 for 2003-2005. P.I. Evaluating the ecological and economic value of the 100th Meridian Initiative.

EPA funding for expert elicitation (about $30,000 expended by EPA under our direction)

Great Lakes Protection Fund. $1,090,000 for July 2006-June 2009. P.I. with Jeff Feder (UND), Chia Chang (UND), John Andersen (The Nature Conservancy), and John Drake (U Georgia). Risk assessment and management of Great Lakes invasive species.

Great Lakes Protection Fund. $805,000 for October 2007-September 2010. P.I. with Jeff Feder (UND), Chia Chang (UND), and Lindsay Chadderton (The Nature Conservancy). Developing and Applying a Portable Real-time Genetic Probe for Detecting Aquatic Invasive Species in Ships' Ballast.

Awards and Honors

Please list all awards and honors received within the time period covered by this annual report.

Acceptance of symposium proposal for AAAS meetings in Chicago in February 2009 on the impacts of shipping NIS in the Great Lakes, during which this work will be prominently highlighted

Patents/Licenses

None

Performance Measures

For each measure, please indicate: (1) what your actual performance was from January 1, 2007 through December 31, 2007; and, (2) your anticipated performance from your start date in 2008 through the following 12 months.

Measure 1: Economic and societal benefits derived from the discovery and application of new sustainable coastal, ocean, and Great Lakes products from the sea.

2007 Actual: None

2008 Anticipated: None

Measure 2: Cumulative number of coastal, marine, and Great Lakes issue-based forecast capabilities developed and used for management.

2007 Actual:

- Forecast the potential North American distribution of Chinese mitten crab (*Erochir sinensis*), which has been introduced to the via shipping, but which is not yet known to have become established.
- Forecast the regions in the US most at risk for invasion by zebra and quagg*a mussels via ov*erland transport away from the Great Lakes region.
- multiple ship-borne invasive species introduced via shipping to the Great L*akes2 new foreca*st capabilities developed
- Employed a research technique novel to the invasion biology community (i.e., *structured exp*ert judgment) to produce impact estimates and uncertainty ranges for the effects of

ship-borne nonindigenous species in the Great Lakes. Quantifying impacts to date informs forecasts of the impacts of future invasions.

2008 Anticipated:

- Implement a regional economic model to estimate the effects of ship-borne nonindigenous species on the welfare of people living in the Great Lakes states and provinces.
- Develop scenarios using the parameterized regional economic model that evaluate various policy options for reducing the likelihood of future invasions.

Measure 3: Percentage/number of tools, technologies, and information services that are used by managers (NOAA and/or its partners and customers) to improve ecosystem-based management.

2007 Actual: None
2008 Anticipated: None

Graphs, figures, photos

FIGURE CAPTIONS

Figure 1. Individual and combined expert assessments showing the impact of ship-borne NIS on US commercial fish landings in 2006 (left column) and 2025 (right column). There are two rows of panels for each lake with the first row showing expert assessments for pounds of commercially landed fish with ship-borne NIS (i.e., actual condition) and the second row showing assessments for how many pounds would have been landed if ship-borne NIS had never been introduced (i.e., hypothetical condition). Dashed lines divide assessments with and without ship-borne NIS. The order of the lakes is, from top to bottom, Superior (a-d), Michigan (e-h), Huron (i-l), Erie (m-p), and Ontario (q-t). Within each panel expert assessments are arranged in order, from top to bottom, Expert 1, 2, 3, 4, 5, 6, 7, 8, 9, equally-weighted combination, and performance-based combination. Vertical light gray bars in panels a, e, i, m, and q show the realization of the variable in question, which was unknown at the time of the elicitation. Note that the scale of the horizontal axis is different for each lake.

Figure 2. Individual and combined expert assessments showing the impact of ship-borne NIS on US sport fishing effort in 2006 (left column) and 2025 (right column). There are two rows of panels for each lake with the first row showing expert assessments for pounds of commercially landed fish with ship-borne NIS (i.e., actual condition) and the second row showing assessments for how many pounds would have been landed if ship-borne NIS had never been introduced (i.e., hypothetical condition). Dashed lines divide assessments with and without ship-borne NIS. The order of the lakes is, from top to bottom, Superior (a-d), Michigan (e-h), Huron (i-l), Erie (m-p), and Ontario (q-t). Within each panel expert assessments are arranged in order, from top to bottom, Expert 1, 2, 3, 4, 5, 6, 7, 8, 9, equally-weighted combination, and performance-based combination. Vertical light gray bars in panels a, e, i, m, and q show the realization of the variable in question, which was unknown at the time of the elicitation. Note that the scale of the horizontal axis is different for each lake.

Figure 3. Individual and combined expert assessments of the impact of ship-borne NIS on US wildlife watching effort in 2006 (left column) and 2025 (right column). The first row shows expert assessments given the presence of ship-borne NIS (i.e., actual condition) and the second row shows assessments for the variable if ship-borne NIS had never been introduced (i.e., hypothetical condition). Dashed lines divide assessments with and without ship-borne NIS. Within each panel, expert assessments are arranged in order, from top to bottom, Expert 1, 2, 3, 4, 5, 6, 7, 8, 9, equally-weighted combination, and performance-based combination. Note that the horizontal axis scale for 2006 versus 2025 is different. The vertical light gray bar in panel a shows the actual number of wildlife watching participant-days in 2006, which was unknown at the time of the elicitation.

Figure 4. Individual and combined expert assessments of the annual per facility impacts of ship-borne NIS on US raw water users in 2006 (left column) and 2025 (right column). The order of the raw water users, from top to bottom, is nuclear power plants (a, b), water treatment plants (c, d), fossil fuel power plants (e, f), and industrial facilities (g, h). Within each panel expert assessments are arranged in order, from top to bottom, Expert 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, equally-weighted combination, and performance-based combination. Note that the horizontal axis scale is different for each user type.

Figure 5. Annual ship-borne NIS percent impacts on US commercial fish landings and recreational fishing effort (panel a) and wildlife watching effort (panel b) for 2006 and 2025. Bar heights indicate percentage by which each quantity would have been greater if ship-borne NIS were not present. Thus, positive values mean the quantity of the variable would have been that percentage higher without ship-borne NIS. Negative values mean that the quantity would have been that percentage lower if there were no ship-borne NIS, indicating enhancement of the variable in the presence of ship-borne NIS. The uncertainty range gives the 5^{th} and 95^{th} percentiles of the distribution of differences between the with- and without-NIS PBC distributions.

FIGURES

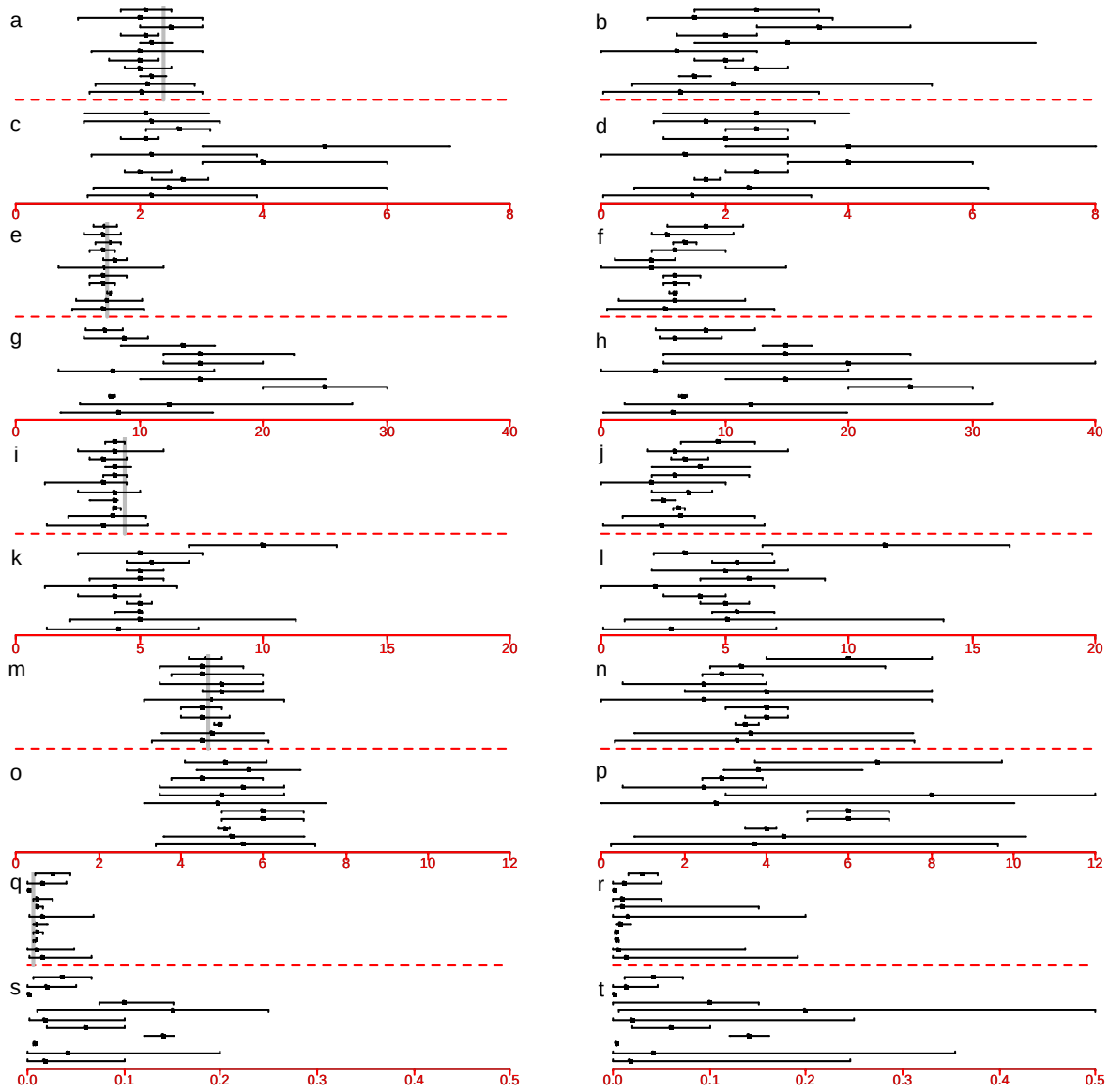
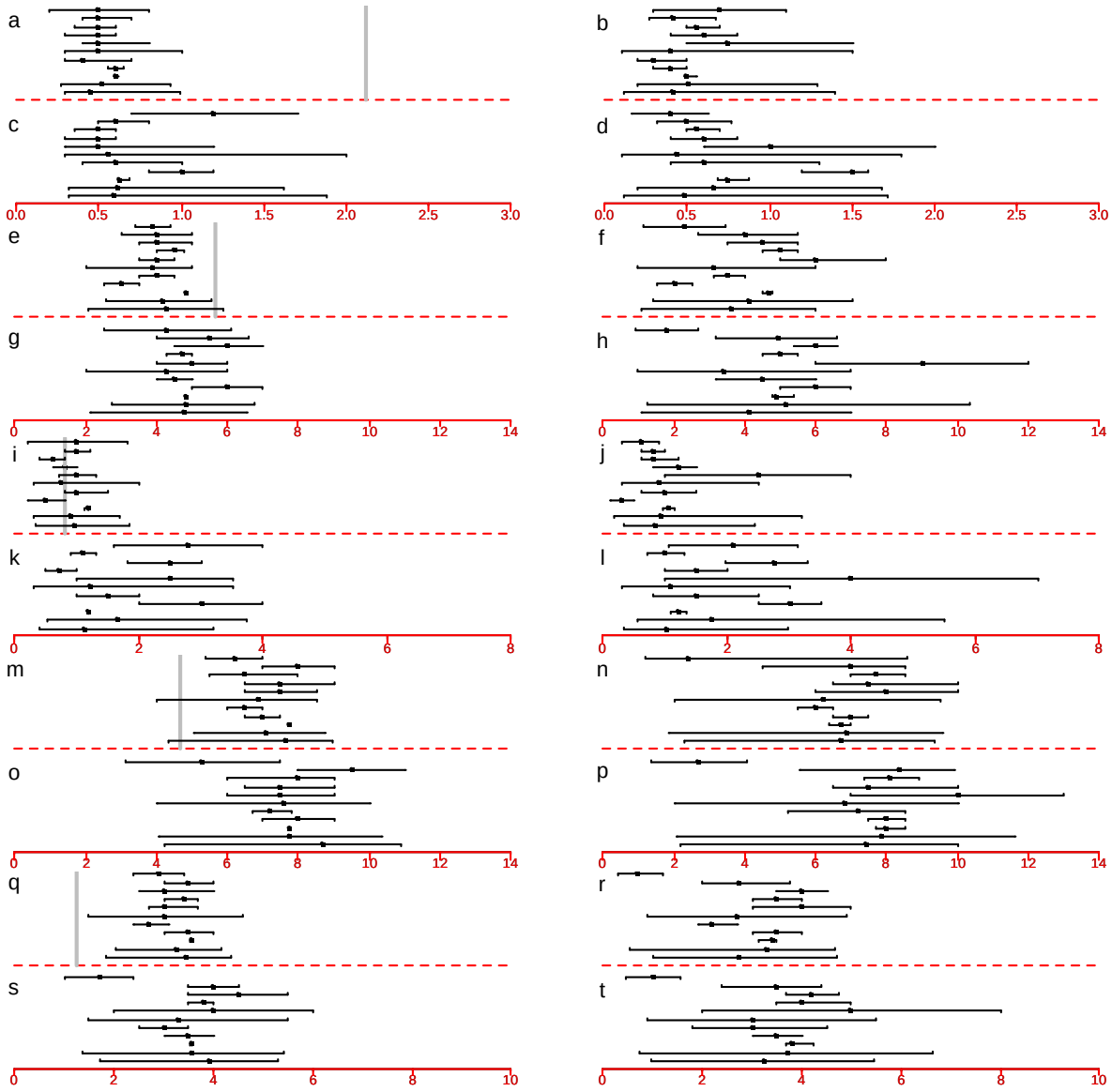


Figure 1.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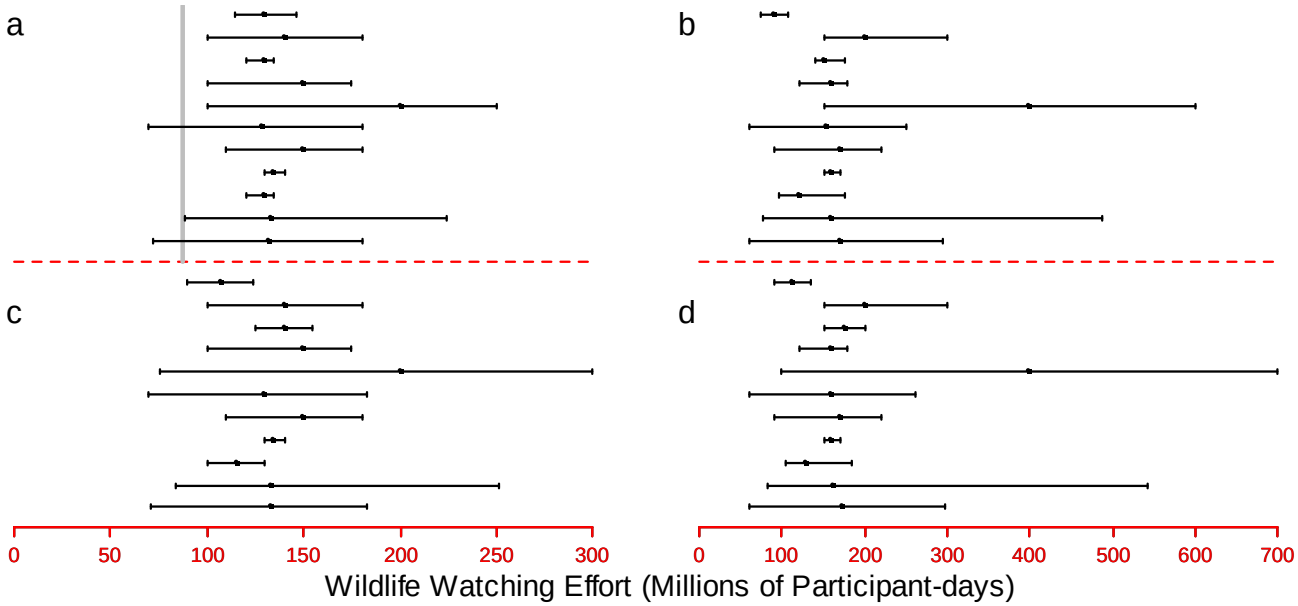
Sport Fishing Effort (Millions of Angler-days)

Figure 2.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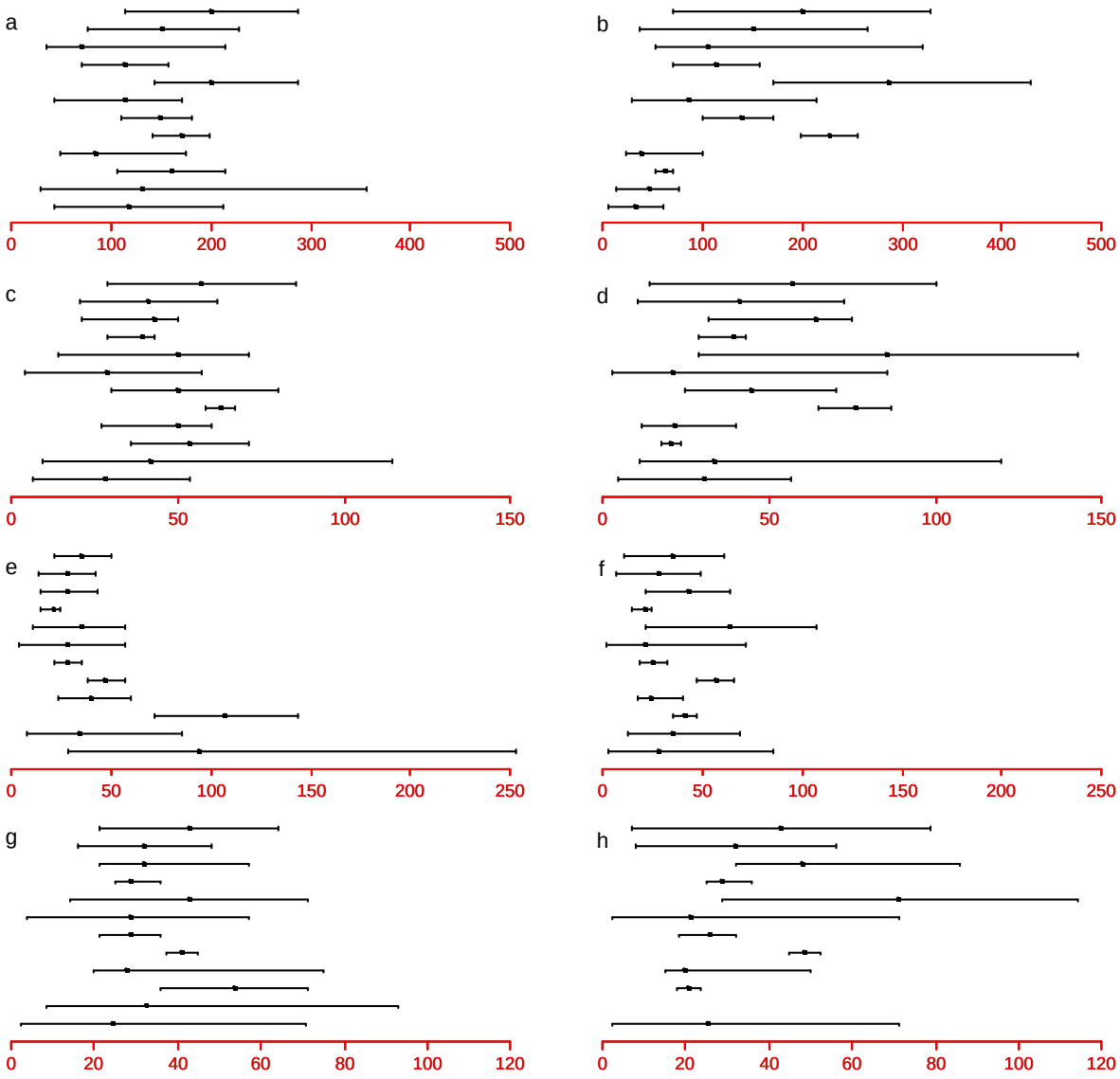
Wildlife Watching Effort (Millions of Participant-days)

Figure 3.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Expense (Thousands of 2007 US $)

Figure 4.

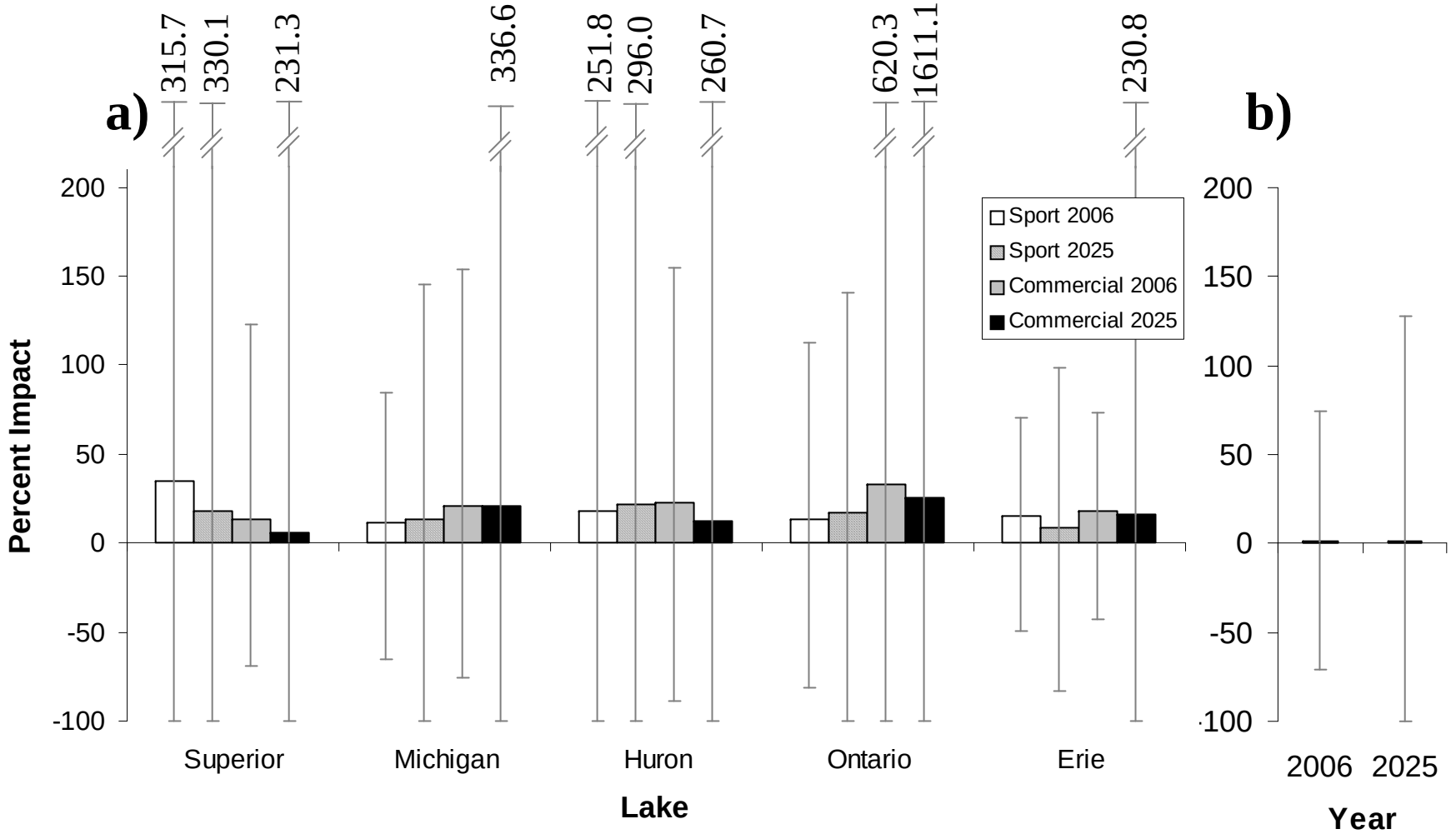
a)
b)
315.7
330.1
231.3
336.6
251.8
296.0
260.7
620.3
1611.1
230.8
Percent Impact
200
150
100
50
0
-50
-100
Sport 2006
Sport 2025
Commercial 2006
Commercial 2025
Superior
Michigan
Huron
Ontario
Erie
Lake
2006
2025
Year

Figure 5.