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Ship-borne Nonindigenous Species Diminish Great Lakes Ecosystem Services

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Abstract

We used structured expert judgment and economic analysis to quantify annual impacts on ecosystem services in the Great Lakes, North America of nonindigenous aquatic species introduced by ocean-going ships. For the US waters, median damages aggregated across multiple ecosystem services were $138 million per year, and there is a 5% chance that for sportfishing alone losses exceeded $800 million annually. Plausible scenarios of future damages in the US waters alone were similar in magnitude to the binational benefits of ocean-going shipping in the Great Lakes, suggesting more serious consideration is warranted for policy options to reduce the risk of future invasions via the St. Lawrence Seaway.

Key words: Laurentian Great Lakes; nonindigenous species; ecosystem services; economic valuation; structured expert judgment; invasive species impacts.

Introduction

Environmental problems often go unaddressed because the value of lost ecosystem services is not expressed in units commensurate with financial investments needed to solve the problem. Invasive species are a leading environmental problem globally (Sala and others 2000), reducing ecological integrity (Carlsson and others 2004), leading to the occasional extinction of native species (Nalepa and others 1996; Mills and others 1994), altering ecosystem functioning (Mills and others 1994), and thereby reducing human welfare via losses of ecosystem goods and services (Pimentel and others 2005). Despite the urgent need to quantify lost ecosystem services, biological and economic researchers using traditional methods struggle to quantify invasive species impacts in units that allow comparisons with the costs of possible private or public remedies. External costs cannot be internalized or otherwise remedied if they are not quantified (Ehrlich and Pringle 2008; NRC 2008).

Here we use structured expert judgment (SEJ) to estimate distributions of the biological and

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economic impacts of nonindigenous species (NIS) introduced to the Laurentian Great Lakes (GL) via ships since the 1959 opening of the St. Lawrence Seaway. SEJ is an established technique for probabilistic risk assessment (Apostolakis 1990; Cooke 1991; Aspinall 2010) and consequence analysis (Cooke and Goossens 2000). It has previously been used for several environmental applications including assessments of the likelihood of natural disasters (for example, volcanic eruption, dam failure; Aspinall and others 2003; Klugel 2011), the consequences of nuclear accidents (Cooke and Goossens 2000), the drivers of climate change (Morgan and others 2006; Lenton and others 2008), expected changes in fisheries and marine ecosystems (Rothlisberger and others 2010; Teck and others 2010) and increases in mortality attributable to air pollution (Roman and others 2008). The method has not previously been used to assess the ecosystem-level impacts of invasive species.

In an SEJ exercise, experts on a topic rely on relevant scientific research and their professional opinions to generate estimates for variables of interest. A key premise of SEJ is that experts can be used as scientific instruments to estimate variables and assess uncertainty when direct measurement is infeasible (Aspinall 2010). The impacts of NIS, for example, could in theory be empirically measured with very large-scale, long-term experiments; in practice, however, logistical, technical, and ethical constraints prevent such experiments (Cooke 1991). Via SEJ, experts estimate the probability distributions for the values of response variables of hypothetical experiments. The structured process explicitly quantifies uncertainty and treats a subset of expert estimates as hypotheses that are tested against data to assess experts' accuracy and their ability to quantify uncertainty. Furthermore, SEJ allows for the combination of judgments from multiple experts into a single distribution for each variable (Cooke 1991).

In this study, we focus on NIS introduced via one vector (that is, shipping) because management efforts, especially those designed to prevent unwanted introductions, are most efficiently focused on vectors (Lodge and others 2006). Globally, shipping is the major vector for aquatic invasive species, including freshwater species (Keller and others 2010). At least 57 alien species introduced by ocean-going ships have become established in the GL, including zebra and quagga mussel (*Dreissena polymorpha* and *D. bugensis*), round goby (*Apollonia melanostomus*), and spiny waterflea (*Bythotrephes longimanus*) (Ricciardi 2006). With more than 35 million people living in the GL basin, ecosystem services from the GL benefit a large number of households and communities, and are part of a substantial regional economy (Austin and others 2007).

To assess the magnitude and uncertainties of impacts associated with the establishment of ship-borne NIS, we consider the US GL region and focus on four ecosystem services that are important to the regional economy and for which reliable historical data are available. These are commercial fish landings, sportfishing participation, wildlife viewing, and raw water usage. In the US in recent years, annual market revenues of commercial fishing in the GL have averaged $15 million (USGS 2008), with yearly expenditures on US GL sportfishing averaging $1.5 billion (USFWS 2007). Nearly 1000 municipal water supplies, industrial facilities, and power generation plants in the US draw raw water from the GL (Deng 1996). Using SEJ, we compare each of these ecosystem services in the current invaded condition to a hypothetical benchmark of an ecosystem state without ship-borne species. In making this comparison, we assume that all other factors (that is, environmental and economic conditions) would have remained exactly the same with and without ship-borne species.

Then, using simple economic methods to estimate consumer surplus, we translate the SEJ impact estimates into dollar values. By converting these impacts into dollar units, we provide benchmarks to inform managers and policy-makers about the predicted consequences of future invasions. These benchmarks could be used to evaluate the benefits of policy and management choices to reduce the probability of future invasions (for example, stringent requirements for ballast water treatment and inspection on ships). Our approach to assessing ecosystem-scale effects of invasive species also provides a template for similar efforts in different ecosystems and for other environmental stressors. Such assessments could be valuable for evaluating policy and management alternatives to prevent or mitigate many kinds of environmental damage.

Methods

Expert Interviews

Through scientific literature review and consultation with senior GL researchers we identified experts who could evaluate the effects of ship-borne NIS in the GL in the context of multiple interacting factors (for example, social trends, economic issues, land-use change, management activities). Ten of these experts participated in our study (Table 1). One expert provided assessments only in regard to

Table 1. List of Participating Experts

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 P. 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 J. Hushak	Professor Emeritus of Agricultural, Environmental and Development 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 basin water treatment facilities, electric power plants and industrial water users
Roger L. Knight	Lake Erie Fisheries Program Administrator for the Ohio Department of Natural Resources, Division of Wildlife. Knight serves on the Lake Erie Committee and the Council of Lake Committees 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 C. Mohr	Fisheries Assessment Team Leader for the Upper Great Lakes Management Unit of the Ontario Ministry of Natural Resources. Mohr has been active in and chaired the GLFC's Lake Huron Technical Committee
Charles R. 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
Donald 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 Evolution, Ecology and Organismal Biology and Director of the Aquatic Ecology Laboratory at The Ohio State University. Stein served as a US Commissioner on the GLFC during 1998–2004

Experts interviewed and the professional title, affiliation, and qualifications of each. Experts are listed in alphabetical order, which does not correspond to the randomly assigned numerical designation of each expert.

biofouling of raw water intakes. For confidentiality, the experts were randomly designated ''Expert 1'' through ''Expert 10.'' The SEJ method we used is not a traditional survey technique and typical concerns about survey sample size are not relevant. In general, the accuracy and informativeness of the combined assessments of multiple experts plateau if at least 10 experts participate (Gehris 2008). We interviewed each expert individually between October 1 and October 19, 2007.

Prior to their interview each expert received the elicitation questionnaire. They also received a booklet with information about NIS in the GL, historical data on fisheries, and training materials on uncertainty and probabilistic assessment. (The booklet and questionnaire are available online at http://environmentalchange.nd.edu/subscribe/publications/.) We encouraged experts to review the booklet prior to their interview and to refer to it as desired during the interview.

We began each interview with a brief presentation about our project, SEJ, and the quantification of uncertainty. The expert then responded to several practice questions similar to those on the questionnaire, receiving immediate feedback as to the true value of the variable being assessed. Our questionnaire asked experts to provide the 5th, 50th, and 95th percentiles of their subjective cumulative probability distribution function for each of 41 variables pertaining to the impacts of ship-borne species on four ecosystem services in 2006. The units of these ecosystem services were pounds of commercially landed fish from the US waters of the GL, angler-days of sportfishing effort on the US waters of the GL, overall expenditures for sportfishing in the US waters of the GL, participant-days of the US wildlife viewing, which encompasses various ecotourism-related activities, and additional costs to raw water users in the GL region of the US.

A typical pair of questions took the following form. First, we asked for the actual value of the variable in 2006 (given that ship-borne species are present). Next, we asked what the value of the variable would have been if ship-borne NIS had never entered the GL.

How many total pounds of commercial fish were landed from the US waters of Lake Erie in 2006?

*5%*__________ *50%*__________ *95%*__________

Suppose ship-borne NIS were NOT present, with all other unrelated ecological and commercial factors unchanged. How many total lbs of commercial fish WOULD HAVE BEEN landed from the US waters of Lake Erie in 2006?

*5%*__________ *50%*__________ *95%*__________

We also recorded the responses of each expert as s/he described his or her thoughts about the mechanisms of ship-borne NIS impacts on each variable.

Performance Measures and Combination of Expert Judgments

We report below the assessments of each individual expert for each variable, as well as combined assessments for each variable. Following Cooke (1991), we combined expert assessments in two ways: (a) each expert's assessment was given equal weight or (b) individual assessments were weighted according to the expert's performance on calibration questions (that is, performance-based combination or PBC). Details on both combination methods appear in the Supplementary Online Materials (SOM).

Of the 41 variables elicited, 12 were calibration variables. These allowed us to assess each expert's statistical accuracy and their ability to express their uncertainty probabilistically. The calibration variables included commercial landings, sportfishing participation and expenditures, and wildlife viewing participation in 2006. The true values of these variables were not known until several months after our interviews.

Ecological and Economic Impacts

We calculated estimates of median percent impacts and the associated 90% uncertainty range by taking the convolution of the joint probabilities of the distributions of the ''without ship-borne species'' PBC minus the ''with ship-borne species'' PBC, assuming independence of all variables. This produced a single distribution of differences between the ''without ship-borne species'' and ''with ship-borne species'' assessment for each variable (for example, sportfishing participation in 2006). We then divided the 5th, 50th, and 95th percentiles of this distribution of differences by the associated median ''with ship-borne species'' PBC assessment and multiplied the quotient by 100 to generate percent impact of ship-borne species.

We applied a benefit approach to capture the economic value of the consequences of ship-borne NIS on the GL region. From an economic viewpoint, if NIS affect the provisioning of ecosystem services, they can result in lost consumer surplus (that is, opportunity costs to consumers). Consumer surplus is the benefit to consumers of a market outcome and accrues whenever consumers pay less than their maximum willingness to pay for a unit of a good. For example, if a consumer is willing to pay $10 per pound for fish and only pays $5, the difference is a measure of the benefit.

To calculate changes in consumer surplus, we used two standard methods under the following assumptions: each estimate was calculated in isolation of the other (that is, neglecting any interaction effects) and under the presumption that everything else (for example, environmental conditions, economic conditions) would have remained exactly the same with and without ship-borne species. Likewise, we assumed society would be willing and able to increase their consumption of less-impaired ecosystem services. Operating under these assumptions, we used a simple market model of demand to assess economic impacts on commercial fishing. For the recreation-based value of sportfishing, we employed a simple benefits transfer method.

For commercial fishing, the elicited values provide predicted quantities of landings with (Q_{in}) and without (Q_{wo}) invaders for each lake. Figure 1 illustrates the case where invaders lead to lower landings. The replacement cost method calculates welfare loss attributable to NIS as lost revenues (Figure 1A, area [$Q_{in}abQ_{wo}$]). This approach assumes that the price per pound of fish remains the same regardless of supply. A more accurate measure of the impact of NIS on consumers is change in consumer surplus, which requires a specification of the market and how the changes in predicted landings are reflected in the market. We assumed that the predicted changes in landings are a result of enhanced (that is, less diminished by invasives) populations of commercially valuable species and

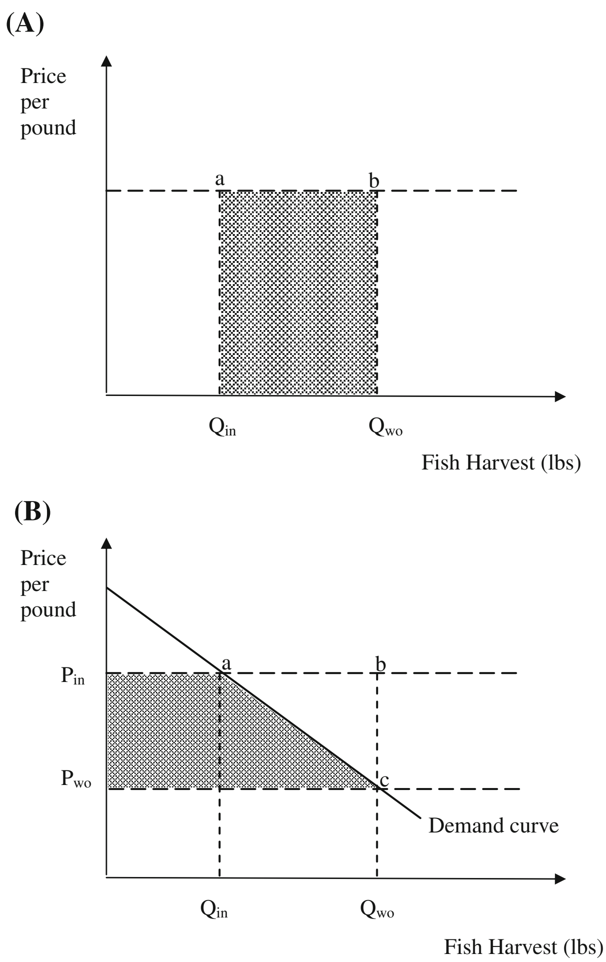

Figure 1. Schematic of social welfare changes related to commercial fishing, illustrating the market model approach taken to estimate economic impacts of ship-borne species. *Vertical axes* measure the price per unit (or pound) of commercial fishing harvests. *Horizontal axes* measure quantities of commercial fishing harvests (in pounds). The demand curve(s) trace out the maximum willingness to pay of consumers for each unit of fish harvested. **A**, **B** illustrate the difference between the replacement cost method (**A** area [$Q_{\text{in}}abQ_{\text{wo}}$]) and the market model method used here (**B**, area [$P_{\text{wo}}P_{\text{in}}ac$]).

these enhancements only serve to increase the quantity landed (that is, they do not result in any change in the consumer demand function). In this restricted view, all that is required additionally is an estimate of the relevant demand curve (Figure 1B).

What is critical about the market method is that the price consumers are willing to pay depends in an inverse fashion upon how much they are able to buy (Figure 1B, demand curve). Thus, if commercial operations would have landed more fish in the absence of ship-borne species, the price consumers would be willing to pay per unit would decline as they bought more fish. The change in consumer surplus is then given by area [$P_{\text{wo}}P_{\text{in}}ac$], which is not necessarily related to the replacement cost (area [$Q_{\text{in}}abQ_{\text{wo}}$]).

The demand curve (Figure 1B) for commercial fishing in each lake provides a means of estimating how the quantity change predicted by the SEJ influences market prices given consumer tastes, which are reflected by their willingness to pay. Although estimating the demand curve for each lake is beyond the scope of this article, an approximation can be made if one assumes demand is linear (as in Figure 1). With this specification the only other data needed are estimates of own-price elasticities of demand, which measure how responsive consumer demand for a good or service is to changes in the price of that good or service. Unfortunately, estimates of this parameter were not available for the aggregated GL fisheries, so we constructed a distribution of estimates of own-price elasticity of demand for fish by accessing all relevant estimates from the USDA's online database (http://www.ers.usda.gov/Data/Elasticities/Query.aspx) and augmenting these with estimates from the seminal work in the literature (Cheng and Capps 1988, summarized in Table 2).

For sportfishing, we viewed predicted changes in participation as an indicator of the difference in the quality of the resources, with (q_{in}) and without (q_{wo}) invaders, which leads to changes in consumption of related goods with (X_{in}) and without (X_{wo}) invaders (Figure 2). For a given price per unit of the related good (P_x) the replacement cost

Table 2. Own-Price Elasticity of Demand for Selected GL Ecosystem Services

	Median	Mean	Standard deviation	Min	Max	Sample size (# estimates)
Category						
Fish elasticity	−0.4772	−0.5235	0.2532	−1.132	−0.0977	27
Sportfishing value	19.35	34.94	42.58	0.26	194.66	53

Summary of values drawn from the literature on own-price elasticity of demand of commercial fish and the value of sportfishing in the GL.

method would calculate the welfare loss as lost revenues due to invaders (area [$X_{in}abX_{wo}$]) as a measure of the welfare loss imposed. Changes in consumer surplus arise because of the change in environmental quality, which shifts the demand curve for the related goods from $D(q_{in})$ to $D(q_{wo})$. The change in consumer surplus is given by the area [*abcd*], which may or may not correspond to the replacement cost estimate.

It is not trivial to estimate the demand for ''related goods'' when that demand is a function of environmental quality. Here we generate these estimates via the benefits transfer methods (Spash and Vatn 2006). We follow the intent of the method in a very simple fashion and use distributions of previously estimated consumer surplus for GL sportfishing in conjunction with the SEJ prediction. We derived per day sportfishing estimates from a query of all GL fishing from the ''Sportfishing Values Database'' (Boyle and others 1998; http://www.indecon.com/fish/).

To assess the distributions of economic impacts on commercial and sportfishing, given uncertainty in economic parameters and in SEJ predictions, we generated joint distributions of the impacts by combining distributions of the SEJ predictions with the distributions of economic parameters, where

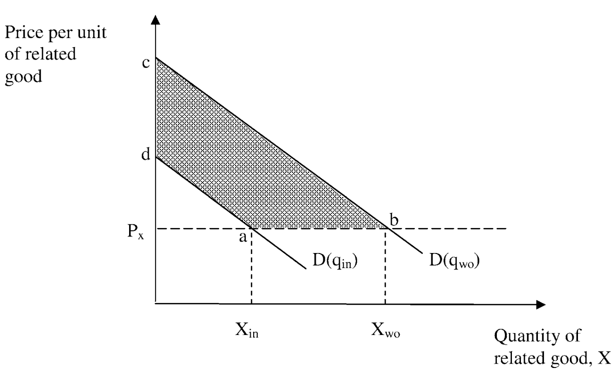

Figure 2. Schematic of social changes related to outdoor recreation, illustrating the inferred market model approach used to estimate economic impacts of ship-borne species. The *vertical axis* measures the price per unit of a good (for example, sportfishing participation) that is related to environmental quality. The *horizontal axis* measures the quantity of the related good (for example, the number of units of sportfishing participation). The demand curves trace out the maximum consumers are willing to pay for the related good, when environmental quality (shown here as q) is low (that is, with invaders, $D(q_{in})$) and the maximum consumers are willing to pay when environmental quality is high (that is, without invaders, $D(q_{wo})$). This diagram depicts a situation where invaders lead to a lower level of environmental quality and thus lower consumption of related goods. Lost consumer surplus is estimated as area [*abcd*].

each distribution was assumed to be independent of all others. For each ecosystem service, 50,000 randomly drawn SEJ prediction values were combined with 50,000 randomly drawn economic parameter values to calculate distributions of the changes in consumer surplus for each ecosystem service.

Without direct knowledge of the true distribution of the economic parameters, we assumed all economic parameters were distributed according to uniform and triangle distributions. These forms are consistent with the limited data available. Most lake-by-lake results are based on the uniform distribution, unless otherwise specified. Joint distributions generated with triangle distributions for economic parameters produced results similar to those generated with uniform distributions.

For raw water usage, we did not perform any economic modeling because the values we elicited from experts were per facility costs resulting directly from biofouling for four different facility types (that is, nuclear power generation plants, fossil fuel power generation plants, industrial facilities, and municipal water plants). We scaled these additional costs from biofouling up to the regional level by multiplying per facility costs by the number of facilities of each type that draw water from the GL in the US (Deng 1996).

Cost-Benefit Forecast

We used our economic impact distributions to compare costs and benefits of potential future ballast water policies. In doing so, we accounted for several related factors. First, our estimates of the cost of invasive species apply to the US only (not including Canada). Second, our results are only a snapshot of dynamic and stochastic invasion processes that have occurred since the opening of the St. Lawrence Seaway in 1959. Third, even the most draconian potential policy of halting the entry of ocean-going ships into the GL would not reduce the impacts we report here because the set of shipborne species we considered would remain in the lakes. Fourth, it is the impact of future invasions that new ballast water policies would affect, but we do not know how the interacting ecological and economic systems of the GL would transition into the future with and without additional invasions.

For comparison with the economic benefits of shipping, we considered four plausible scenarios of how economic impacts might accumulate if current shipping patterns and ballast water releases remain unchanged. Under each scenario, we compared the costs of invasions to the benefits of shipping.

Estimates of shipping benefits came from a previous study of the St. Lawrence Seaway that found that it provides annual transportation savings of $58 million (in 2007 USD) over using other transport modes (for example, truck or rail) to move the goods and materials that are currently carried into the GL region on ocean-going ships (Taylor and Roach 2009).

Selecting an appropriate discount rate for cost-benefit forecasting remains an open discussion among economists (Heal 2009). Therefore, in our analysis, we considered the consequences of several discount rates (1, 3, 6, 9, and 12%).

One plausible scenario of future ship-borne species damages (''Constant Increase'') is that impacts from new invasive species will grow at the same constant average annual rate over the next 50 years as they did in the past (assuming linearly increasing impacts during the previous 5 decades (that is, $138 million in 2006 divided by 48 years of accumulating impacts ≈$3 million growth in impacts per year).

Another plausible scenario (''Growing Increase'') has annual impacts growing at an accelerating rate according to the formula $x_t = x_{t-1} + b + c(t - 1)$, where x_t is the annual impact in year t, b is the base rate of impact growth, and c is amount by which the added impact grows from 1 year to the next. We set the base rate of impact growth (b) to be the same as the linear model of impact growth (that is, $3 M) and c to be $0.1 M.

We also considered a scenario where additional annual impacts of invasions accrue at a decreasing rate (''Decreasing Increase until Plateau,''), eventually reaching a plateau at which annual impacts remain the same from 1 year to the next. To illustrate this scenario, we selected an annual rate of decrease of $100,000 and a plateau of $50 M above the $138 M/year level in 2006. In a fourth plausible scenario (''Exponential Increase''), we assume that additional annual impacts will grow exponentially from $0 to $138 M/year over the next 50 years.

Results

Performance and Combination of Expert Judgments

In all categories, for any given variable, uncertainty ranges varied substantially across individual experts (SOM Figures 1, 2, 3). Relative uncertainty ranges appeared to depend more on the individual expert than on the variable being assessed. Uncertainty was almost universally greater for ''without ship-borne species'' assessments than for ''with ship-borne species'' assessments. Combined assessments for a given variable ''with'' and ''without ship-borne species'' differed more from one another than did the assessments of any single expert for the same ''without-with'' pair (SOM Figures 1, 2, 3).

Equal weighting and PBC of expert assessments produced similar results with respect to median percent impacts. The equal-weighted combination, however, was not statistically accurate ($P < 0.05$), but the PBC was statistically accurate (that is, the null hypothesis of statistical accuracy of the PBC

Table 3. Performance and Combination of Expert Judgments

Expert or combination	*P* value	Mean relative information	Normalized weight	
			Nonoptimized	Optimized
1	4.029E−5	0.9401	0.000196	0
2	0.09646	0.7019	0.3501	0.3524
3	0.0001173	1.2590	0.000763	0
4	0.0001173	1.0030	0.000608	0
5	0.0007465	1.1310	0.00436	0
6	0.4539	0.2741	0.6433	0.6476
7	0.0001173	0.9895	0.000600	0
8	4.856E−6	1.3670	3.432E−05	0
9	1.912E−9	2.8600	2.828E−08	0
EQUAL	0.04411	0.3066	–	–
PBC (nonoptimized)	0.9281	0.2061	–	–
PBC (optimized)	0.9281	0.2086	–	–

Calibration, informativeness, and weights of experts, their equal-weighted combination (EQUAL), and their PBC. Higher P values (Column 2) and higher mean relative information scores (Column 3) indicate better performance in assessing the calibration variables accurately and precisely, respectively; accuracy is much more important than precision for assigning expert weights in the PBC. Experts whose P value is less than the optimal significance level (8E−4) are not included in the optimized PBC (see SOM Methods). Columns 4 and 5, respectively, show the relative contribution of each expert to the nonoptimized and optimized PBC.

could not be rejected; Table 3, SOM Methods). The *P* values of individual experts are quite uneven, with only Experts 2 and 6 exhibiting good individual statistical accuracy. Thus, the optimized PBC included only the assessments of these two well-calibrated experts (that is, 2 and 6).

It is a common misunderstanding that increasing the number of experts in a SEJ study and the subsequent PBC confers the same benefits associated with increasing the sample size of a survey. This is not true. As mentioned above, the equal weight combination of these 10 experts was not statistically acceptable. The goal of obtaining statistically acceptable and informative results was achieved by positively weighting only two well-calibrated experts. For this reason and for brevity, we report here the results of the PBC. We focus on median values because, by definition, experts considered these impacts most likely.

Ecological and Economic Impacts

Distributions predicted by experts indicate that without ship-borne NIS the GL would be providing larger commercial fishery harvests and more participation in sportfishing, with median damage estimates ranging among lakes from 13 to 33% in commercial fisheries and 11 to 35% in sport fisheries (Table 4; Figure 3). Because of large discrepancies among expert assessments of impacts on sportfishing in L. Superior, and lacking a reliable calibration variable for these assessments, the 35% impact estimated for L. Superior lacks sufficient support to be included in our calculation of economic impacts below. The sport fishery of L. Superior is small relative to the sport fisheries of the other GL and therefore more volatile than those of the other lakes in terms of percent impacts. There were also large discrepancies among the experts as to median impacts on L. Superior sportfishing, with several indicating zero impact from ship-borne species, but with others estimating impacts at 70–150% (SOM Figure 1). These discrepancies reduced our confidence in the PBC median impact assessment for this variable. Other studies show that L. Superior has been relatively minimally impacted by ship-borne species (Grigorovich and others 2003).

For wildlife viewing, experts' uncertainties are very large and participation levels are just as likely to decrease as to increase without ship-borne NIS in the GL (Table 4; Figure 3). Given these equivocal impact estimates and the extreme uncertainty, we did not include wildlife viewing in our economic analyses.

Experts provided mechanistic explanations for their assessments of current and future impacts (see SOM Results). Although some experts described some aspects of the impacts of selected NIS as positive, almost never did an expert indicate that the median value of an ecosystem service variable would be greater with ship-borne NIS than without. Nevertheless the distribution of the PBC of estimated impacts for all ecosystem services includes values to the left of zero, denoting possible beneficial effects of ship-borne NIS (Figure 3). This is largely an artifact of our simplifying assumption of independence between pairs of elicited variables

Table 4. Percent Impacts of Ship-borne Species on GL Ecosystem Services

Ecosystem service	Lake	Median % impact estimate	% of Distribution above	
			0% Impact	100% Impact
Commercial fishing	Superior	13	59	9
	Michigan	21	62	16
	Huron	23	62	16
	Erie	18	68	1
	Ontario	33	57	39
Sportfishing	Superior	35	66	35
	Michigan	11	59	2
	Huron	30	62	31
	Erie	15	65	1
	Ontario	14	62	2
Wildlife viewing	All	1	51	2

Distributions of percent impacts of ship-borne nonindigenous species on ecosystem services of the GL in the US. Impacts are summarized as median damage estimates and % of the impact distribution above 0% impact and 100% impact. Impact values are the percentages by which the ecosystem service metric (for example, pounds of fish commercially landed, angler-days of sportfishing, participant-days of wildlife viewing) would have been greater if no ship-borne nonindigenous species had invaded the GL since the 1959 opening of the St. Lawrence Seaway.

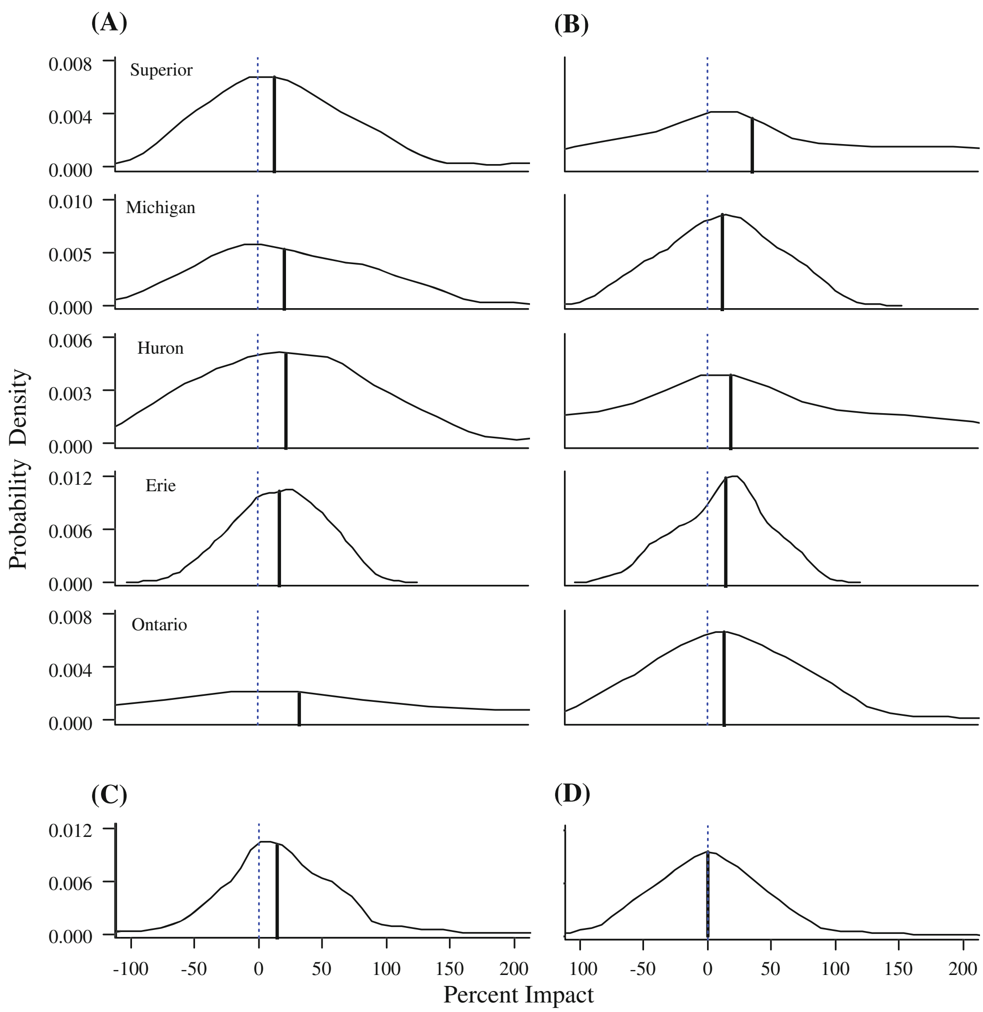

Figure 3. Distributions of ship-borne species percent impacts on **A** US commercial fish landings (for each lake), **B** sportfishing effort (for each lake) and **C** expenditures (aggregated across all five lakes), and **D** wildlife viewing effort (aggregated across all five lakes) in 2006. Distributions are PBCs of expert assessments. *Dashed lines* indicate zero, whereas *solid black lines* designate medians, indicating the most likely percentage by which each quantity would have been greater if ship-borne species were not present. Commercial landings, sportfishing effort, and wildlife viewing effort are summarized in Table 4.

for the actual case (with ship-borne species) and the counterfactual case (without ship-borne species). The independence assumption overestimates uncertainty, broadening the resulting distributions. Converting these impact distributions into economic impacts (as changes in consumer surplus) introduces an additional layer of uncertainty. Thus, the distributions of economic impacts are wider than those of the SEJ results alone (Figure 4 vs. 3).

For the commercial fishery, economic impacts are likely greater than zero, with a median loss of $5.3 million (Figure 4A). The estimated median economic impact on sportfishing of $106 million is greater than for commercial fishing, although sportfishing impact distributions reflect a greater degree of uncertainty (Figure 4B, SOM Results). For biofouling impacts on raw water use, median additional operating costs aggregated over all GL facilities is $27 million (Figure 4C). Among water users, the municipal water treatment sector experiences the greatest losses (as calculated by the number of facilities in the region multiplied by additional costs per facility), whereas nuclear power generation experiences the least (Table 5). Combining these three ecosystem service sectors, the estimated overall median economic losses were $138.3 million.

However, considering sportfishing alone—a large economic sector for which expert distributions were skewed strongly in the direction of negative impacts—a 5% chance exists that impacts are as high as $800 million (Figure 5).

Cost-Benefit Forecast

The discount rate is a key variable in our cost-benefit forecast because it determines if and how long it will take for damages from ship-borne NIS to exceed transportation savings from shipping. We focus here on results based on a 3% discount rate, which is the rate currently used for US federal water projects (http://go.usa.gov/XtM), but we also consider higher and lower rates. As discount rate

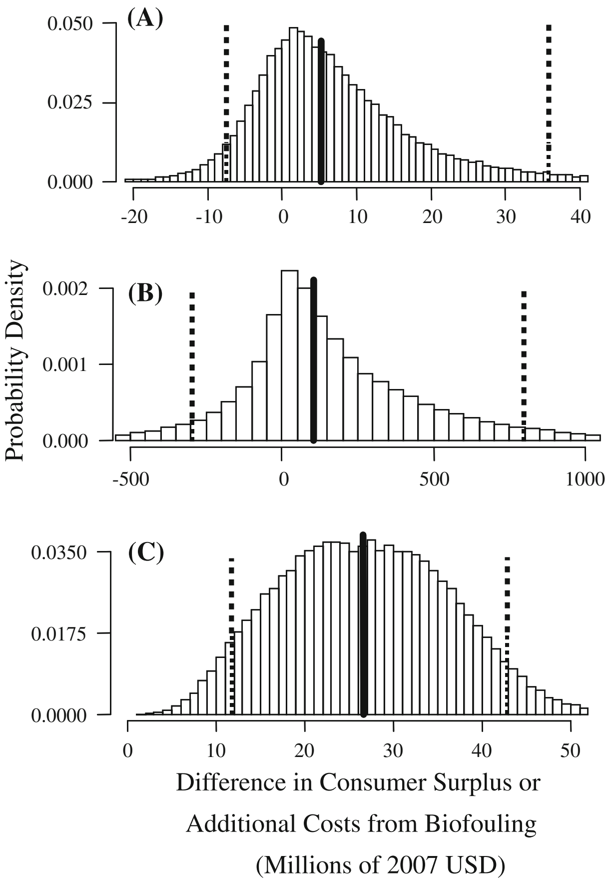

Figure 4. Distributions of economic impacts as lost consumer surplus (fishing) or additional costs (raw water users), aggregated across lakes, of ship-borne nonindigenous species on ecosystem services in the GL in the US. **A** commercial fishing, **B** sportfishing, and **C** raw water use. *Solid black lines* indicate the median and *dotted lines* the 90% uncertainty range of each distribution. Note differences in scale of horizontal and vertical axes of plots.

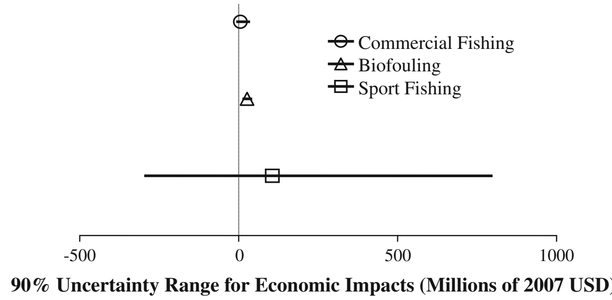

Figure 5. Ninety percent uncertainty ranges for economic impacts in the United States of ship-borne NIS on multiple ecosystem services in the GL.

increases it takes longer for cumulative damages to exceed cumulative savings (Table 6). For example, under the ''Growing Increase'' scenario of future damages, cumulative damages and savings are equal after 30 years given a 1% discount rate versus after 44 years with a 6% discount rate. Under the assumption of a 9 or 12% discount rate, damages never exceed savings. In other words, if the analyst does not care much about the future (that is, s/he selects high discount rate) then the transportation savings will dominate the cost-benefit analysis. The more the future matters (for example, the discount rate will be 0% if future welfare is as important as present welfare), the more the damages from invasive species matter in the analysis.

On the benefit side, carrying the annual transportation savings from Taylor and Roach (2009) 50 years into the future with a 3% discount rate yields $1.41 billion in cumulative transportation savings.

For the ''Constant Increase'' scenario of future damages with a 3% discount rate, preventing future ship-borne invasions would avoid the cumulative loss in the US of more than $1.45 billion in ecosystem services over the next half century (Figure 6). In this case, a moratorium on the passage of ocean-going ships in the St. Lawrence

Table 5. Additional Annual Operating Costs to Raw Water Users

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)
Fossil fuel power plant	2006	28.1	(6.6, 53.5)	260[1]	7.31	(1.72, 13.91)
Municipal water plant	2006	32.5	(4.9, 61.3)	436[2]	14.17	(2.14, 26.73)
Industrial facility	2006	30.4	(4.6, 56.7)	117[2]	3.56	(0.54, 6.63)
Total	2006	–	–	–	26.57	(4.96, 50.02)

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

[1]*Power plants in the GL Basin, Northeast Midwest Institute Report (http://www.nemw.org/images/stories/documents/Power%20plants%20in%20the%20Great%20Lakes%20Basin.pdf, accessed 11/4/2011).*

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

Table 6. Years until Cumulative Invasive Damage Exceeds Cumulative Transportation Savings

Discount rate (%)	Alternative invasive damage scenarios			
	Growing increase	Constant increase	Decreasing increase until plateau	Exponential increase (from $0 to $150 M/y)
1	30	40	–	57
3	33	49	–	63
6	44	–	–	81
9	–	–	–	135
12	–	–	–	–

The effect of discount rate on the number of years after stopping ocean-going ships from entering the GL at which cumulative invasive damage exceeds cumulative transportation savings under four scenarios of possible increases in damage from invasive species. Discount rates reflect the value of present welfare relative to that of future welfare, with higher rates placing increasingly more value on the present. Dashes indicate combinations of scenario and discount rate where damages never exceed savings.

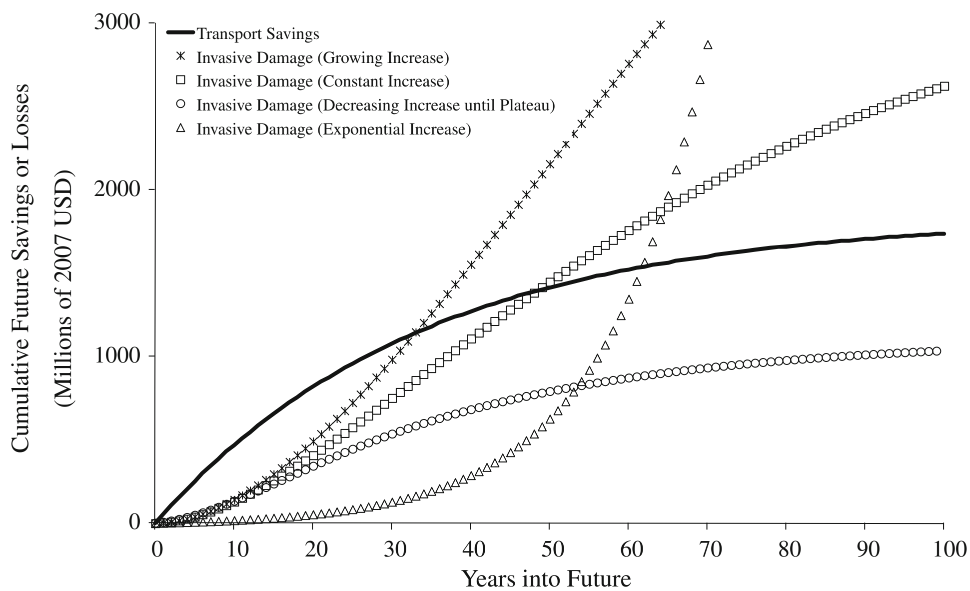

Figure 6. Four alternative scenarios of future cumulative ship-borne invasive species damage relative to cumulative transportation savings from ocean-going shipping into the GL.

Seaway, the most draconian measure proposed to stop future ship-borne invasions in the GL, would not produce net benefits until 49 years in the future (Figure 6).

For the ''Growing Increase'' scenario of future damages, the additional cumulative losses from ship-borne invasions over the next 50 years ($2.16 B) would be $750 million more than transportation savings from shipping, with cumulative damages becoming greater than cumulative savings after 33 years (Table 6).

For the ''Decreasing Increase until Plateau'' scenario of future damages, if and when the cumulative damages become greater than cumulative savings depends on the discount rate, the rate of annual decrease ($100,000 in this example), and the level at which impacts plateau (here $50 M above the $138 M/year level in 2006). This $188 M plateau is likely near the low end of the range of plausible plateaus, given that much of the distribution of damages estimated for 2006 is above $188 M (Figure 4). For the ''Exponential Increase'' scenario, cumulative losses from ship-borne NIS do not surpass cumulative transportation savings until 63 years into the future (Figure 6; Table 6). In reality, annual impacts of invasions must eventually level off either at a state of utter ecosystem degradation when there is no value left to lose or when the impacts of any future invaders are completely redundant with existing impacts.

Discussion

This study provides ecosystem-scale estimated distributions of the US bioeconomic impacts of invasive species introduced via a specific vector. Analyses like the one we report here can help to address the consequences of biological invasions in units that can inform more rigorous benefit-cost analyses of alternative policies to prevent future invasions. By explicitly quantifying uncertainty inherent in both the biological and the economic systems, we have enabled policy-makers to make choices about prevention policies with fuller than usual knowledge about risks of future damages.

Because the value of commerce, including the shipping commerce considered here, is obvious and often well quantified, policy decisions made without information on ecosystem services tend to strongly discount the negative environmental side effects of commerce. Although the range of our estimates of the collective impact of invasive species are large, our median estimates (that is, the impact levels experts thought most likely) and the scenarios for the accumulation of future economic damage suggest that substantial new investments in reducing ship-borne invasions in the GL are warranted.

Previous estimates of the impacts of invasive species in the GL have concentrated on raw water users (NRC 2008; O'Neill 1996). Experts in this study indicate that these impacts persist but are small relative to impacts on other ecosystem services. Specifically, although our study shows that the economic consequences of ship-borne invasions for the US sportfishing are highly uncertain, the median impact assessment on this valuable ecosystem service is large, and the majority of the impact distribution (60%) is greater than zero. Because sportfishing is a relatively large economic sector, it provides the bulk of the predicted median impacts. Our study provides a fuller understanding of the impacts of ship-borne NIS on the US GL regional economy with respect to declines in valuable recreational opportunities like sportfishing.

Ideally, estimates of biological and economic damage attributable to alien species would result from empirical measurements and comparisons of key response variables before and after the invasion, while controlling for all other simultaneously changing factors and conditions that could affect the response variables (Hoagland and Jin 2006). Obtaining such data for the GL region is not possible, making it necessary to seek an alternative approach to quantifying damage to ecosystem services. In SEJ, we found a workable approach to estimate invasive species impacts, representing an important advance because it is highly structured, clearly documented, and explicitly quantifies uncertainty. Quantifying uncertainty in problems like the one we consider here, where data are limited and where the broad-scale experiments needed to better understand the problem are intractable, and yet where decisions hinge on understanding the problem and our collective understanding of it, is as, if not more, important than the accuracy of the median values (Aspinall 2010).

Some of the previous efforts to quantify the economic impacts of invasive species have been poorly documented, sometimes reporting worst-case scenarios as actual impacts (Hoagland and Jin 2006). Misleading estimates of the economic impacts of invasive species can promote policies that are fiscally wasteful (Hoagland and Jin 2006), highlighting the value of transparent methodologies like those we employed here. Moreover, the simple market models we used to estimate economic impacts are an improvement over previous studies that use replacement cost methods to determine the economic impact of invasive species. The replacement cost method often employed in estimating the value of lost economic activity is the product of current market price and a change in the available quantity of a good or service. However, market prices capture only a snapshot of the relative rate at which the market is willing to exchange one good for another. Outputs of the replacement cost method tend to be rejected as valid estimates of economic impact because they have no relationship to surplus measures (for example, consumer surplus), which assess changes in welfare (Phaneuf and Smith 2005). However, as shown here, estimating economic surplus can be a challenge because it requires more information than market prices and quantities.

Although market-based methods for commercial fishing are straightforward, determining changes in the value of sportfishing is more complicated. The problem is that when considering an outdoor recreation activity like sportfishing, the goods are not traded in well-defined markets (as are fish caught commercially), preventing the use of a market model. The usual method employed to deal with the first problem (that is, missing markets) is to focus on related goods. That is, there are complementary goods that consumers purchase when recreating (that is, expenditures on time and travel) and these goods are traded in markets. The likely answer to the second question (that is, what drives the change) is that an improvement in quality of the resource (that is, improvements in environmental quality) leads to increased demand for outdoor recreation (and complementary goods) and vice versa. This method, which we employ, assumes that the effects of changes in the consumption of complementary goods (arising from a change in environmental quality) provide an indirect indication of the value of recreation. This assumption of ''weak complementarity'' provides the basis of a large amount of research in environmental economics (Palmquist 2005; Spash and Vatn 2006).

Several aspects of our work make it likely that our median impact estimates are lower than actual damages. First, we did not include damages to ecosystem services in the Canadian portion of the GL basin, where the largest commercial fishery exists. Second, we did not include several large US economic sectors (for example, recreational boating, beach use) that are affected by ship-borne invasions. Third, we did not consider losses to ecosystem services that are in the US but outside the GL region. Unlike other forms of pollution, these living species continue to increase in abundance, spread, and further reduce ecosystem goods and services throughout the continent (Drake and Bossenbroek 2004; Bossenbroek and others 2007). The dreissenid mussel invasion of Lake Mead and various California waterways is one such example that is ultimately attributable to shipping in the GL (Stokstad 2007).

Additional research could further clarify the net value of alternative policies designed to prevent future invasions. First, the ecological efficacy of current ballast water management strategies require further evaluation, especially because of the absence of systematic surveillance programs for invasive species in receiving waters (Costello and others 2007; Bailey and others 2011). Without a surveillance program, it is impossible to have confidence that recent trends in species discovery (Bailey and others 2011) indicate that ballast water exchange has been effective (Costello and others 2007). Second, future studies could elicit information on the dependence of distributions with and without invaders, thus avoiding the assumption that these distributions are independent and reducing uncertainty in the results (Cooke and Goossens 2000). Third, more research is needed on the size and the economic characteristics (for example, supply and demand curves) of the sportfishing sector. Finally, a better understanding of the accumulation of impacts from ship-borne NIS up to the present and into the future, and how alternative technologies and policies may change the accumulation of impacts would allow for more fully informed scenario analysis (NRC 2011; EPA 2011).

This study focuses on the valuation of ecosystems or, more precisely, their decrease in value, in terms of dollars. However, the value of ecosystems cannot be expressed entirely in monetary units. For example, existence values of natural resources have been described in the economic literature (Krutilla 1967; Kneese 1984; Cicchetti and Wilde 1992). Furthermore, some argue that natural objects have something akin to rights and that respect for these rights should guide their management and conservation (Stone 1972; Goulder and Kennedy 2011). With these perspectives in mind, we acknowledge that dollar valuation does not express completely the importance of functioning ecosystems. Dollar values are, however, one facet of the benefits of ecosystems and the services they provide to society. By describing ecosystem degradation in units of dollars, as we do here, we allow for comparison of that degradation with other losses or gains associated with economic activities that are also measured in dollars. We recognize, however, that as only a fraction of the multi-faceted value of ecosystems, the dollar values presented here represent a lower bound on the damage and disruption associated with invasive species, especially because they do not include damages on the Canadian side of the GL.

Completely stopping the introduction of invasive species to the GL via ocean-going vessels is unlikely (NRC 2008, 2011; Bailey and others 2011; EPA 2011). Nevertheless, our study provides a useful estimate of the value, in terms of likely damage to ecosystem services avoided, of efforts to prevent future invasions by ship-borne species. We narrowed the focus of our study to estimate the economic impacts arising from ecological perturbations caused by invasive species in a particular system, the GL, associated with a particular introduction vector, shipping. Estimates of the impacts of species delivered via a certain vector can support decision-making regarding vector-based policy and management. Our estimates of economic impact provide a figure for comparison against the costs of implementing management activities to prevent invasions via the shipping pathway. Comparison of our results with the results of an earlier study on the transportation savings from shipping (Taylor and Roach 2009; Figure 6) illustrates how our results might be used to evaluate alternative ballast water-treatment policies like those considered in studies by the US National Research Council (NRC 2011) and the US Environmental Protection Agency (EPA 2011). Whether or not net savings will result from the prevention of future invasions will depend on the cost of modifying transportation systems and on how the magnitude of invasive species impacts change in the future. Learning the rate at which annual impacts may change in the future and where these impacts are likely to plateau is an important next step for evaluating ballast water policy and management.

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