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POLICY ANALYSIS

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Evaluating Efficacy of an Environmental Policy to Prevent Biological Invasions

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S Supporting Information

ABSTRACT: Enactment of any environmental policy should be followed by an evaluation of its efficacy to ensure optimal utilization of limited resources, yet measuring the success of these policies can be a challenging task owing to a dearth of data and confounding factors. We examine the efficacy of ballast water policies enacted to prevent biological invasions in the Laurentian Great Lakes. We utilize four criteria to assess the efficacy of this environmental regulation: (1) Is the prescribed management action demonstrably effective? (2) Is the management action effective under operational conditions? (3) Can compliance be achieved on a broad scale? (4) Are desired changes observed in the environment? The four lines of evidence resulting from this analysis indicate that the Great Lakes ballast water management program provides robust, but not complete, protection against ship-mediated biological invasions. Our analysis also indicates that corresponding inspection and enforcement efforts should be undertaken to ensure that environmental policies translate into increased environmental protection. Similar programs could be implemented immediately around the world to protect the biodiversity of the many freshwater ecosystems which receive ballast water discharges by international vessels. This general framework can be extended to evaluate efficacy of other environmental policies.

INTRODUCTION

The introduction of nonindigenous species (NIS) is recognized as a leading cause of global biotic homogenization and extinction.[1−3] As a result, environmental managers are under increasing pressure to establish comprehensive programs to prevent, control, and eradicate NIS, with prevention playing a key role.[4−6] Evaluating the efficacy of any environmental policy, such as regulations aimed at preventing introduction of NIS, is essential for productive management decisions, especially under a changing regulatory environment and inadequate funding.[5,7] Measuring the success of an environmental policy, however, is a challenging task even for intensively regulated industries for which decades of data are available.[8,9] Evaluating regulations targeting prevention of NIS introductions is particularly problematic owing to a dearth of comparative data [4,10] and the difficult task of confirming that a potentially unknown species has been removed from a transportation vector. The objective of this study is to examine the efficacy of ballast water policies enacted to prevent biological invasions in the Laurentian Great Lakes.

The Great Lakes' ballast water management program is the most comprehensive globally which, if proven effective, could be immediately emulated internationally to protect and conserve the biotic integrity of the many freshwater ecosystems that receive ballast discharges by international ships. We outline a series of four questions, prioritized from small- to large-scale, to assess the efficacy of this environmental policy:

(1) Is the prescribed management action demonstrably effective?

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(2) Is the management action effective under operational conditions?
(3) Can compliance be achieved on a broad scale?
(4) Are desired changes observed in the environment?

We suggest that initial assessments should concentrate on empirical "cause and effect" studies to confirm that the prescribed management action does achieve the desired effect. Once direct results are demonstrated, the focus should expand to monitoring operational efficacy, to confirm that the prescribed action is equally effective under less controlled operational conditions. Ideally, these studies should be conducted prior to implementation of any regulations. Third, compliance rates should be assessed to determine if any perceived inefficacy is due to noncompliance. Finally, broad trends of environmental improvement can be measured, as this is generally not meaningful until the first three criteria have been examined; furthermore, it may not be possible to assess environmental trends without many years of data, preferably both pre- and postimplementation of regulatory policies.[10] While we examine the Ballast Water Management Program for the Great Lakes as a case study, this general framework can be extended to evaluate efficacy of other environmental policies that prescribe a management action.

Great Lakes' Ballast Water Management Program. Transoceanic shipping activities are attributed with ∼55−70% of an estimated 56 aquatic NIS invasions recorded in the Great Lakes since 1959.[11,12] Following the discovery of the Eurasian ruffe (*Gymnocephalus cernuus*) in 1988, the Canadian and U.S. federal governments enacted voluntary and mandatory regulations in 1989 and 1993, respectively, which required all foreign ballast water to be exchanged for midocean saltwater.[13,14] Ballast water exchange (BWE) should reduce invasion risk by reducing the propagule pressure, or number of individuals, released with ballast water discharge by physically purging individuals from tanks, or by destroying retained individuals through osmotic shock.[15,16]

Since all vessels transiting into the Great Lakes must cross both Canadian and American jurisdictions, the 1993 regulations effectively applied to the entire Great Lakes basin. The discovery of new aquatic NIS during the late 1990s and early 21st century suggested that BWE was ineffective and/or that alternate vectors were operational.[10,17]

Until recently, vessels were only required to manage tanks with declared ballast on board, since tanks with no declarable ballast on board (NOBOB) were considered "empty" by industry standards. However, studies revealed that NOBOB vessels dominated transoceanic vessel traffic arriving to the Great Lakes, and that the flora and fauna carried in residual ballast could be discharged during multiport operations.[18,19] In response, the U.S. Coast Guard recommended voluntary management of residual ballast by flushing NOBOB tanks with ocean saltwater.[20] Tank flushing involves using a small volume, typically 7−20% of tank capacity, of midocean saltwater to purge residual ballast water and sediments from tanks. Beginning in June 2006, Canada required all foreign vessels entering the Great Lakes to exchange and/or flush all ballast tanks, achieving a minimum final salinity of 30‰.[21] The St. Lawrence Seaway Corporations implemented consistent regulations in March 2008, thereby harmonizing American and Canadian standards.[22]

A joint binational ballast water inspection program was created in 2005 to streamline enforcement activities. Inspections begin with a review of ballast water reporting forms submitted by vessels prior to arrival; ships reporting unmanaged ballast are instructed to conduct exchange and/or flushing while still offshore. A physical visit to the ship is then conducted on arrival to inspect ballast water logs and management plans, and to assess crew competency. Finally, a ballast tank exam is conducted, wherein the salinity of ballast water is measured.

■ EXAMINATION OF POLICY EFFICACY

1. Does BWE/Flushing Reduce Propagule Pressure? Ballast water exchange and flushing are protective, particularly for freshwater habitats, because of the dual effect of physical removal and mortality due to osmotic stress. Empirical studies suggest that BWE typically results in 70−95% physical removal of coastal marine plankton,[15,23] while osmotic stress for freshwater or estuarine species can eliminate a further 40−88% of taxa not purged from tanks.[24] A retrospective analysis of aquatic NIS recently introduced to the Great Lakes indicated that all eight species tested would not have survived BWE, if the length of salinity exposure was at least 72 h.[16]

A study examining four ships carrying freshwater ballast from the Great Lakes to European ports found BWE to be 95.1 to 100% effective.[25] We utilized hierarchical Bayesian analysis to further examine data from this study, providing two main advantages over previous frequentist methods (e.g., Analysis of Variance): First, it allowed us to examine the possible variability of actual invertebrate density in the ballast water, given the data, rather than assuming observed data occurred without error. Thus, instead of assuming 100% efficacy for some tanks, we could examine the probability of observing no species for each possible true density. Second, given the observed data, we could estimate the distribution of efficacies across the population of ships. In so doing, we simultaneously used information across ships to inform the likely values for each ship. For instance, if we found no propagules across many ships, we would be more certain that the underlying density was close to zero than if we had treated each ship in isolation.

We first estimated the density of Great Lakes' zooplankton in a given tank, both before (λ_b) and after (λ_e) BWE, assuming data from three subsamples at each time period was the result of random sampling and a Poisson distribution of organisms. Efficacy was then derived for each of four vessel trips:

$$(E = \lambda_e/\lambda_b) \tag{1}$$

Next, we assumed the four ships sampled were a random representation of the vessel population. Formally,

$$pr(\alpha, \beta, \boldsymbol{\lambda}|\mathbf{N}) \propto L(\lambda|\mathbf{N})L(\alpha, \beta|\boldsymbol{\lambda})pr(\alpha, \beta) \tag{2}$$

$$\text{pmf}\left(\mathbf{N}_{b,i} \middle| \lambda_{b,1}\right) = \frac{e^{-\lambda_{bi}}\lambda_{bi}^{\mathbf{N}_{bi}}}{\mathbf{N}_{bi}!} \tag{3}$$

$$\text{pdf}\left(E_b \middle| \alpha, \beta\right) = \frac{1}{B(\alpha, \beta)} E_b^{\alpha-1}(1 - E_b)^{\beta-1} \tag{4}$$

where L is the likelihood obtained from pmf/pdf (eqs 3 and 4), pr is the probability, $\mathbf{N}$ is the vector of observations of number of organisms from all ships, before and after BWE, and λ is the vector of true densities (eq 2). α and β are shape parameters that define the beta distribution, which will determine the population distribution of λ across ships, based on the data. We converted λ into proportion E (comparing before and after BWE *within* each ship), so that we could use the beta distribution to determine exchange efficiencies across ships. Specifically, for

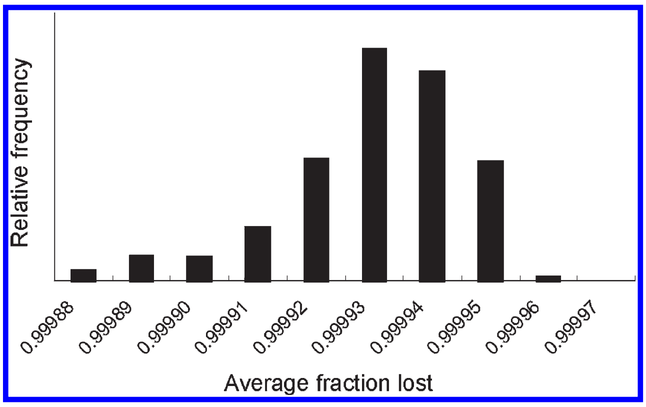

Figure 1. Relative frequency of ballast water exchange efficacy against freshwater invertebrates, as modeled by Bayesian analysis of data from Gray et al.[25]

each set of α and β, we calculated the average efficacy across all ships by integrating across the beta distribution (mean = $\alpha/(\alpha+\beta)$). We assume a noninformative uniform prior. We used Markov Chain Monte Carlo simulation with a burn-in period of 1 million iterations, and characterized the posterior probability distribution with 1 million iterations.

The modeled efficacy of BWE between freshwater ports, based on observed plankton densities, was remarkably high. The average proportion of individuals expected to be lost across all ships as a result of the combined effects of physical purging and osmotic stress ranged from 99.988% to 99.997%, with a mode of 99.993% (Figure 1). The cumulative evidence from the above cause and effect studies indicates that the prescribed management practices of BWE or flushing can effectively decrease propagule pressure in freshwater ballast.

2. Is BWE/Flushing Effective under Operational Conditions?

To determine if BWE and flushing remain effective when implemented without highly controlled conditions, we opportunistically sampled 19 NOBOB tanks on 15 vessels, and 24 ballasted tanks on 16 vessels from transoceanic and coastal ships arriving to the Great Lakes between November 2005 and May 2008. NOBOB tanks were sampled by filtering 50 L residual water through a 53 μm mesh plankton net; sampling methodology was similar to that of an earlier study,[26] allowing comparison of results before and after introduction of flushing regulations. Ballasted tanks were typically sampled by lowering a plankton net into full tanks, such that at least 1000 L of water was filtered for analysis; methodology was similar to that of earlier studies,[27,28] allowing comparison of results before and after introduction of BWE regulations.

We explored differences in taxonomic composition of samples for NOBOB and ballasted tanks separately. For all analyses, plankton densities were averaged for tanks within ships, since these cannot be considered independent samples.[29] Following Duggan et al.,[26] we recognize that measures of total invertebrate abundance may overestimate effective invasion risk, thus we conducted additional comparisons using only "high risk" species. Species were defined as high risk for establishment in the Great Lakes if any global population of the taxon was previously recorded from fresh or brackish waters, which we conservatively defined as salinities of ≤18‰, and included all taxa sampled from tanks containing fresh or brackish water by default. Analyses were conducted using a Mann−Whitney U-test since data could not be transformed to meet assumptions of parametric tests. A significance level of 0.05 was utilized for all analyses; all statistical

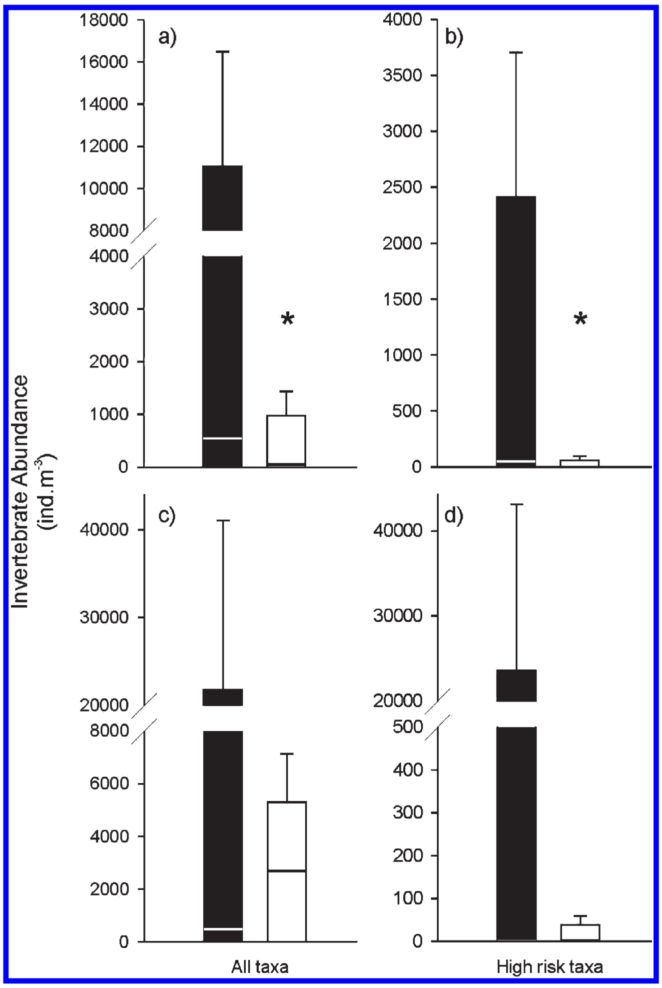

Figure 2. Mean (+S.E.) abundance of invertebrates recorded from "no ballast on board" (upper panels) and ballasted (lower panels) ships, before (black bars) and after (white bars) the introduction of saltwater flushing and ballast water exchange, respectively. Median values are indicated by horizontal lines superimposed on bars. Left panels include data for all taxa; right panels present data only for high risk taxa known to inhabit fresh- or brackish-water habitats. Data for preregulatory period from Duggan et al.,[26] Bio-Environmental Services[27] and Locke et al.[28]

comparisons were conducted using JMP 7.0.2 (2007 SAS Institute).

Our limited sampling program indicates that the benefits of BWE and flushing are retained under operational conditions. The abundance of all invertebrates (range 0.0 to 5440.0 ind·m^{-3}; median 60.0 ind. m^{-3}) and of high risk invertebrates (range 0.0 to 426.7 ind·m^{-3}; median 0.0 ind·m^{-3}) sampled from residual ballast water after flushing regulations were in place were significantly lower than in preregulation samples (Mann−Whitney U test, p = 0.032 and p = 0.035, respectively; Figure 2a,b). While no freshwater organisms were sampled postflushing, four of nine taxa identified to species level have been recorded in brackish waters including *Acartia* nr. *clausi*, *Paracalanus parvus*, *Pseudocalanus minutus*, and *Oithona similis* (Supporting Information (SI) Appendix S1). Salinity of residual water from which these taxa were sampled exceeded 30‰ in four of six cases, indicative of successful tank flushing in the open ocean. Similarly, total abundance of invertebrates collected from ballasted tanks ranged from 40.0 to 26220.0 ind·m^{-3} (median 2672.9 ind·m^{-3}), while that of

Table 1. Summary Statistics of Ballast Water Salinity, By Tank, As Measured during Ballast Tank Exams in 2005-2007[a]

	2005				2006				2007			
	NOBOB		ballasted		NOBOB		ballasted		NOBOB		ballasted	
	no.	%	no.	%	no.	%	no.	%	no.	%	no.	%
number of compliant vessel transits	59	49.2	10	38.5	143	73.3	20	51.3	102	77.9	70	77.8
number of noncompliant vessel transits	61	50.8	16	61.5	52	26.7	19	48.7	29	22.1	20	22.3
total number of compliant tanks (≥30‰)	579	73.2	125	67.6	1585	90.4	410	85.4	1365	94.3	1382	97.4
total number of noncompliant tanks[b]	212	26.8	60	32.4	168	9.6	70	14.6	83	5.7	37	2.6
number of tanks at 0 - <5‰	15	7.1	5	8.3	11	6.5	18	25.7	24	28.9	6	16.2
number of tanks at 5 - <18‰	108	50.9	27	45.0	88	52.4	31	44.3	31	37.4	11	29.7
number of tanks at 18 - <30‰	89	42.0	28	46.7	69	41.1	21	30.0	28	33.7	20	54.1

[a] NOBOB tanks contain only residual ballast, whereas ballasted tanks carry large volumes of ballast water. [b] "Dry" tanks, from which no water was retrieved, were excluded from analysis.

high risk invertebrates ranged from 0.0 to 280.5 ind. m^{-3} (median 1.0 ind·m^{-3}). Comparison with preregulation studies indicates that mean and maximum density of invertebrates in ballasted tanks have been reduced, particularly for high risk taxa, although median density has not changed significantly (Mann−Whitney U test, p = 0.060 and p = 0.70 for all and high risk taxa, respectively; Figure 2c, d). Two freshwater taxa (*Daphnia* spp., and *Diaphanosoma* sp.) and five species recorded from brackish water (*Acartia tonsa*, *Amphiascus* sp., *Eurytemora hirudinoides*, *Pseudodiaptomus coronatus*, and *Crangon septemspinosa*) were observed, typically at very low abundance and occurrence (SI Appendix S1).

Considering the median density of high risk taxa recorded after BWE and flushing, the effective invasion risk for freshwater ports may frequently be equivalent to that expected with ballast water discharge standards developed by the International Maritime Organization (less than 10 individuals·m^{-3} for all organisms greater than 50 μm in minimum dimension).[30] Although maximum densities can be an order of magnitude greater than the international standard, the dramatic decreases in the probability of a single introduction event with extremely high plankton density may be highly relevant, since rare high-density introduction events are thought to be extremely important for new invasions.[31] Further, the cumulative propagule pressure over time likely has also decreased, resulting in further reduction of invasion risk. Reduced propagule pressure should decrease invasion success, however, there exists an urgent need to determine if a critical threshold population density exists below which invasions fail. Allee effects can be pronounced when populations are founded by few colonizers,[32] though this effect might be offset if the colonizers are capable of parthenogenetic reproduction.[33]

3. Do Most Vessels Comply with BWE/Flushing Regulations? To determine if the general vessel population complies with ballast water management regulations, we analyzed data from ballast water reporting forms and ballast tank exam forms collected under the joint inspection program during 2005−2007, inclusive. Reporting forms provided self-reported data on ballast history for individual vessel transits, while tank exam forms provided measurements of ballast water salinity and volume, as measured by Inspectors; salinity measurements ≥30‰ were compliant with ballast water management regulations. Ballast tank exams conducted by U.S. Inspectors prior to 2005, and independent of the joint program in 2005−2007, comprised an important contribution to Great Lakes' inspection efforts; however, because the proportion of tanks inspected was much more

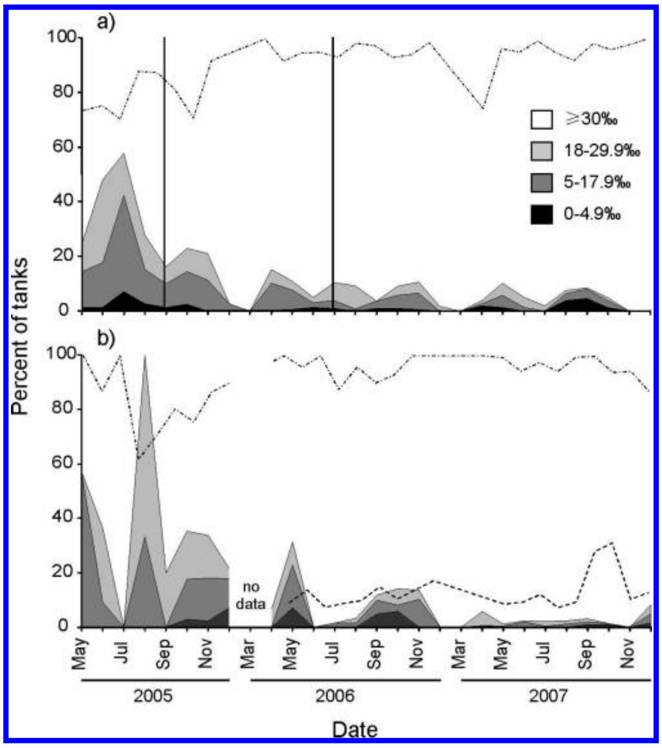

Figure 3. Salinity of ballast water measured from tanks on vessels classified as (a) "no ballast on board" and (b) ballasted, expressed as a percentage of all tanks inspected, by month. The percent of tanks inspected per ship, by month, under the joint (dot-dashed lines) and independent (dashed line) inspection programs is indicated. Solid vertical lines in panel (a) indicate date of introduction of U.S. voluntary NOBOB management practices (31 Aug 2005), and Canadian mandatory (28 June 2006) NOBOB regulations.

limited than under the joint program (typically 2 tanks per ballasted vessel), they are not included in our analysis.

Data was assembled for each vessel transit originating outside Canadian waters and examined using both a ship-wise and tank-wise perspective, since regulations were implemented on a ship-wise basis prior to June 2006 and on a tank-wise basis thereafter. For ship-wise analysis, vessels were classified following definitions used by Transport Canada, wherein ballasted vessels carried ≥200 tonnes of ballast water and/or had at least one main tank containing ≥10% of its ballast water capacity, whereas NOBOB vessels carried <200 tonnes of ballast water and had no main tank containing ≥10% of its ballast capacity. The proportion of transoceanic and coastal vessels given physical ballast tank exams increased from 66% in 2005, to 87% in 2006 and 2007, although only 602 reports were recovered for this analysis (56% of all joint tank exams; 45% of the vessel population) (SI Appendix S2). Examination of ballast volumes indicates that the median volume of residual ballast water carried by NOBOB vessels was 24 tonnes per ship, or 1.4 tonnes per tank, with a small proportion of vessels (3−16%) having at least one auxiliary tank in ballast (SI Appendix S3). Similarly, ballasted vessels do not arrive to the Great Lakes fully loaded with ballast water, but tend to have less than 25% of tanks in ballast (SI Appendix S3).

The number of vessels with all tanks compliant increased steadily over time coincident with the implementation of education and inspection programs (Table 1; Figure 3). The proportion of tanks on NOBOB vessels containing euhaline (≥30‰ salinity) ballast water increased from 73% in 2005 to 94% in 2007. The sharpest increase in residual ballast salinity coincided with the introduction of voluntary NOBOB management practices in August 2005 (Figure 3a). The number of "dry" tanks, from which no water was retrieved to measure salinity, decreased from nearly 60% of all tanks inspected in 2005 to 33% in 2007 (SI Appendix S2). This decrease may reflect increased ballast management activities since tanks managed in the mid-Atlantic prior to Great Lakes entry should not be subject to the high rates of evaporation common in warmer climates. Dry ballast tanks may indicate that tank flushing did not occur prior to entry, although vessels equipped with stripping systems may remove virtually all ballast from tanks. Therefore, the ability of vessels to physically strip tanks dry should be evaluated and/or physical tank entry during inspection may be warranted to determine risk if salinity cannot be measured from the vessel's deck. Given that the proportion of tanks on ballasted vessels with euhaline ballast water increased from 68% in 2005 to 97% in 2007, coincident with a change in inspection effort but not regulatory change, it appears that the level of enforcement of regulations is closely linked to compliance (Table 1; Figure 3b).[34]

We used tank exam data to determine the level of inspection effort required to detect a single noncompliant tank on a vessel, with 95% confidence, using the probability model:

$$P = 1 - \prod_{i=0}^{s-1} \left(1 - \frac{a}{n-i}\right) \quad (5)$$

where s is the number of sampled tanks, n is the number of tanks on a vessel, a is the number of tanks noncompliant, and P is the probability of detecting at least one tank given the sampling effort applied. Approximately half of all tanks containing noncompliant ballast water were the result of incomplete management, where exchange or flushing was conducted but the required 30‰ salinity was not achieved. Noncompliant vessels typically contained only one or two tanks in violation. As a result, 20 of 21 tanks must be inspected to detect a single noncompliant tank, or 16 of 21 tanks if two noncompliant tanks are present, to have 95% confidence in results of the inspection program. Conversely, if only one or two tanks are inspected per vessel, there is a 90−95% chance that noncompliant tanks will be missed.

4. Has Invasion Rate of NIS Declined in the Great Lakes? Ideally, implementation of an environmental policy will be followed by improvement(s) in environmental condition. With respect to biological invasions, the relevant outcome would be a

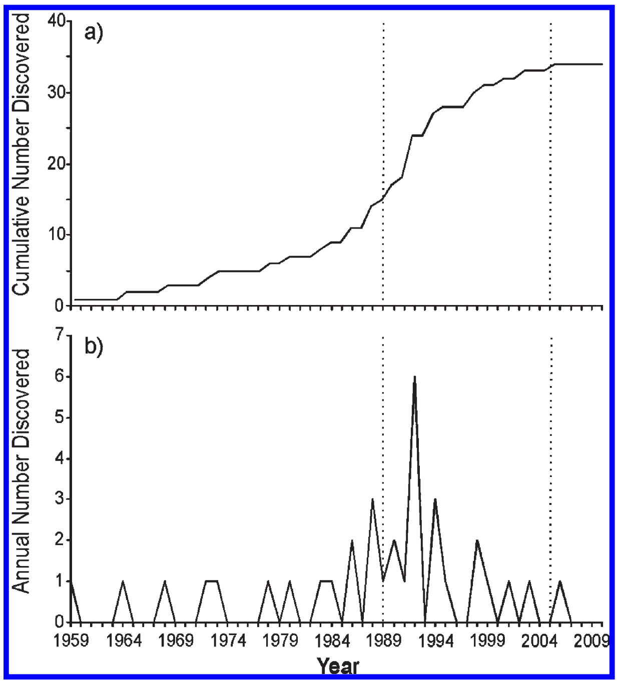

Figure 4. (a) Cumulative number and (b) annual number of ship-mediated aquatic invasive species discovered in the Great Lakes between 1959 and 2010, inclusive. Dotted vertical lines indicate date of introduction of Canadian voluntary ballast water exchange (1989) and U.S. voluntary tank flushing (2005) management practices, respectively.

reduction in the rate of new species introductions to the system. Examining invasion rates, however, requires many years of data to form conclusions with any certainty.[10] We can now attempt this analysis with 20 years of data postregulation, though we acknowledge that analyses of discovery rate are confounded by time lags (where there is a gap between the date of introduction and the date of discovery), inconsistent research effort, taxonomic bias, and insufficient data. As a result, discovery rate analyses are meaningful only in combination with the prior three questions.

We assembled data on dates of discovery of ship-mediated aquatic NIS reported in the Great Lakes after the opening of the modern St. Lawrence Seaway in 1959. We followed the conservative approach of Kelly et al.,[35] who excluded cryptogenic species whose status as native or nonindigenous is uncertain. The cumulative number and annual number of NIS discovered over time was graphed and visually inspected to determine if the rate of discovery changed after implementation of ballast water regulations. Segmented regression was subsequently utilized to determine the location of the inflection or "change" point.[36] Twelve points of interest were tested (1986−1997) and the fit characterized by the sum of the error sums of squares; the point with the lowest combined sum of the error sums of squares was considered as the point of change in the discovery rate of aquatic NIS.

Our analysis revealed 34 aquatic ship-mediated NIS reported from the Great Lakes after 1959 (Figure 4a). The rate of aquatic NIS discovery was relatively linear between 1959 and the mid-1980s, after which time it began to increase. The peak number of discoveries occurred in 1992 when six NIS were reported, including five parasitic species associated with the Eurasion ruffe (Figure 4b); the discovery rate begins to decline rapidly after the peak. Segmented regression identified 1991 as the most significant change point, which appears to correspond with the date that discovery rate began to increase. Post-1991, 1995 was identified as the most likely point of decline in discovery rate. This inflection point may correspond with a six year time lag after the inception of voluntary ballast water management in 1989, or a two year time lag after implementation of mandatory BWE regulations. Since 2000, shipping activities have been responsible for three of eight (37.5%) aquatic NIS introductions and no new species have been reported since 2006; this is the first time there has been a four-year gap in ship-mediated aquatic NIS discoveries since 1974−1977, indicating that tank flushing regulations may have been an important addition to the management regime. A third inflection point corresponding with effects of tank flushing regulations may exist; however, several more years of data are required to identify any such point with confidence.

DISCUSSION

Implementation of environmental policies should include an assessment to gauge efficacy of changes made to human behavior to ensure management resources are used most effectively. Our comprehensive assessment of the Great Lakes' ballast water management program, using four lines of evidence, indicates that the risk of ship-mediated aquatic NIS introductions has been markedly reduced. First, comprehensive laboratory and shipboard studies indicate that BWE and tank flushing can effectively decrease the number of viable propagules in ballast tanks. Modeling indicates that the combined effects of tank purging and osmotic shock are typically 99.993% effective at removing or exterminating freshwater zooplankton. Second, biological monitoring data confirms that at the operational level, BWE and flushing significantly reduce the probability for rare, high density, introduction events and nearly eliminate high risk taxa. Third, compliance rates by the general vessel population appear very high, perhaps a direct result of the intensive inspection regime. Only 4.2% of ∼2850 tanks tested in 2007 contained ballast water with a salinity <30‰ and, because they were detected by inspectors, were prohibited from being discharged into the Great Lakes. Our analysis indicates that these noncompliant tanks would not be detected at lower inspection effort levels, thus it is very important to maintain intensive inspection efforts to retain confidence in this management regime. Finally, examination of the discovery rate of aquatic NIS in the Great Lakes basin supports a decline in ship-mediated introductions following the initiation of the ballast water management program.

We acknowledge that ballast water can transport a variety of active and dormant taxa, ranging from microbes and bacteria to fishes and large sessile invertebrates.[37−39] A complementary study examining efficacy of tank flushing on dormant invertebrate eggs in ballast sediments under operational conditions found significant reductions in total egg density, viable egg density, and density of eggs of high risk NIS.[40] Unfortunately, a dearth of data precludes assessment of the Great Lakes ballast water management regulations with respect to other taxa. Even so, it is clear that the prescribed management strategies will not provide complete protection against aquatic invasions, since a large percentage reduction can still result in substantial propagule pressure if initial densities were high. Total propagule pressure, however, is not reflective of the effective invasion risk for Great Lakes ports, since many marine taxa will not be able to survive if introduced into fresh water. Considering that the median density of high risk taxa recorded after BWE and flushing is 0.0 to 1.0 ind·m^{-3}, the effective invasion risk for freshwater ports may frequently approximate the same level of protection expected under the ballast water discharge standards developed by the International Maritime Organization.[31] As ballast water treatment systems utilizing technologies such as ozonation, chlorination and/or filtration are not expected to be implemented on all vessels until 2016, similar ballast water management programs could be implemented immediately around the world to protect the biodiversity of the many freshwater ecosystems which receive ballast water discharges by international vessels (e.g., Antwerp, Rotterdam, Constanta, Gdansk, St. Petersburg).

The St. Lawrence River provides an ideal "choke-point" for entry to the Great Lakes from which inspection stations can and do operate to the benefit of the entire basin. While ballast salinity is the main indicator used to enforce ballast regulations, it is not foolproof, as many coastal ports have salinity levels that are indistinguishable from that of ocean water. Secure, geo-referenced and automated reporting of ballast water exchange locations for each tank could eliminate uncertainty of ballast management history, while reducing inspection costs and ship delays.[12] Although inspection programs can be expensive, the cost of inaction is likely far higher: while Transport Canada alone spends $1.6 million annually for ship inspections, costs of aquatic NIS in the Great Lakes amount to at least $200 million per year.[41] Changes to environmental policy should be enacted in concert with tools to inspect and enforce regulations or there will be little opportunity to measure, or to expect, program success. The framework of questions outlined in this analysis could be extended to evaluate efficacy of numerous other environmental policies that mandate changes in operational practices, such as requirements for wastewater treatment systems or industrial exhaust scrubbers to reduce point-source pollution, by directly assessing cause and effect of the prescribed technologies, compliance rates, and changes in the environment.

ASSOCIATED CONTENT

Supporting Information. A list of taxa identified during biological sampling, data on inspection rates, and ballast water volume of inspected vessels are available online (Appendices S1, S2, and S3, respectively.) The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author. This material is available free of charge via the Internet at http://pubs.acs.org.

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