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Evaluating Efficacy of an Environmental Policy to Prevent Biological 1 Invasions 2

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ABSTRACT: Enactment of any environmental policy should 13 be followed by an evaluation of its efficacy to ensure optimal 14 utilization of limited resources, yet measuring the success of 15 these policies can be a challenging task owing to a dearth of data 16 and confounding factors. We examine the efficacy of ballast 17 water policies enacted to prevent biological invasions in the 18 Laurentian Great Lakes. We utilize four criteria to assess the 19 efficacy of this environmental regulation: (1) Is the prescribed 20 management action demonstrably effective? (2) Is the manage-21 ment action effective under operational conditions? (3) Can 22 compliance be achieved on a broad scale? (4) Are desired 23 changes observed in the environment? The four lines of 24 evidence resulting from this analysis indicate that the Great 25 Lakes ballast water management program provides robust, but 26 not complete, protection against ship-mediated biological in-27



vasions. Our analysis also indicates that corresponding inspection and enforcement efforts should be undertaken to ensure that 28 environmental policies translate into increased environmental protection. Similar programs could be implemented immediately 29 around the world to protect the biodiversity of the many freshwater ecosystems which receive ballast water discharges by 30 international vessels. This general framework can be extended to evaluate efficacy of other environmental policies. 31

■ INTRODUCTION 33

The introduction of nonindigenous species (NIS) is recognized as 34 a leading cause of global biotic homogenization and extinction.^{1–3} As 35 a result, environmental managers are under increasing pressure to 36 establish comprehensive programs to prevent, control, and eradicate 37 NIS, with prevention playing a key role.⁴⁻⁶ Evaluating the efficacy of 38 any environmental policy, such as regulations aimed at preventing 39 introduction of NIS, is essential for productive management deci-40 sions, especially under a changing regulatory environment and inadequate funding.^{5,7} Measuring the success of an environmental 41 42 policy, however, is a challenging task even for intensively regulated 43 industries for which decades of data are available.^{8,9} Evaluating 44 regulations targeting prevention of NIS introductions is particularly 45 problematic owing to a dearth of comparative data 4,10 and the 46 difficult task of confirming that a potentially unknown species has 47 48 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?

Received:	August 4, 2010
Accepted:	February 23, 2011
Revised:	February 22, 2011

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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 64 empirical "cause and effect" studies to confirm that the prescribed 65 management action does achieve the desired effect. Once direct 66 results are demonstrated, the focus should expand to monitoring 67 operational efficacy, to confirm that the prescribed action is 68 equally effective under less controlled operational conditions. 69 Ideally, these studies should be conducted prior to implementa-70 71 tion of any regulations. Third, compliance rates should be assessed to determine if any perceived inefficacy is due to 72 noncompliance. Finally, broad trends of environmental improve-73 ment can be measured, although this is generally not meaningful 74 until the first three criteria have been examined; furthermore, it 75 may not be possible to assess environmental trends without 76 many years of data, preferably both pre- and postimplementation 77 of regulatory policies.¹⁰ While we examine the ballast water 78 management programs for the Great Lakes as a case study, this 79 general framework can be extended to evaluate efficacy of other 80 environmental policies that prescribe a management action. 81

Great Lakes' Ballast Water Management Program. Trans-82 oceanic shipping activities are attributed with \sim 55-70% of an 83 estimated 56 aquatic NIS invasions recorded in the Great Lakes 84 since 1959.11,12 Following the discovery of the Eurasian ruffe 85 (Gymnocephalus cernuus) in 1988, the Canadian and U.S. federal 86 governments enacted voluntary and mandatory regulations in 1989 87 and 1993, respectively, which required all foreign ballast water to be 88 exchanged for midocean saltwater.^{13,14} Ballast water exchange 89 (BWE) should reduce invasion risk by reducing the propagule 90 pressure, or number of individuals, released with ballast water 91 discharge by physically purging individuals from tanks, or by destroying retained individuals through osmotic shock.^{15,16} 92 93

Since all vessels transiting into the Great Lakes must cross 94 both Canadian and American jurisdictions, the 1993 regulations 95 effectively applied to the entire Great Lakes basin. The discovery 96 of new aquatic NIS during the late 1990s and early 21st century 97 suggested that BWE was ineffective and/or that alternate vectors 98 were operational.^{10,17} 99

100 Until recently, vessels were only required to manage tanks with 101 declared ballast on board, since tanks with no declarable ballast on board (NOBOB) were considered "empty" by industry standards. 102 However, studies revealed that NOBOB vessels dominated transo-103 ceanic vessel traffic arriving to the Great Lakes, and that the flora and 104 fauna carried in residual ballast could be discharged during multiport 105 operations.^{18,19} In response, the U.S. Coast Guard recommended 106 voluntary management of residual ballast by flushing NOBOB tanks 107 with ocean saltwater.²⁰ Tank flushing involves using a small volume, 108 typically 7-20% of tank capacity, of midocean saltwater to purge 109 residual ballast water and sediments from tanks. Beginning in June 110 2006, Canada required all foreign vessels entering the Great Lakes to 111 exchange and/or flush all ballast tanks, achieving a minimum final 112 salinity of 30‰.²¹ The St. Lawrence Seaway Corporations imple-113 mented consistent regulations in March 2008, thereby harmonizing 114 American and Canadian standards.²² 115

A joint binational ballast water inspection program was created in 116 117 2005 to streamline enforcement activities. Inspections begin with a review of ballast water reporting forms submitted by vessels prior to 118 arrival; ships reporting unmanaged ballast are instructed to conduct 119 exchange and/or flushing while still offshore. A physical visit to the 120

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. 124

■ 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 136 the Great Lakes to European ports found BWE to be 95.1 to 137 100% effective.²⁵ We utilized hierarchical Bayesian analysis to 138 further examine data from this study, providing two main 139 advantages over previous frequentist methods (e.g., Analysis of 140 Variance): First, it allowed us to examine the possible variability 141 of actual invertebrate density in the ballast water, given the data, 142 rather than assuming observed data occurred without error. 143 Thus, instead of assuming 100% efficacy for some tanks, we 144 could examine the probability of observing no species for each 145 possible true density. Second, given the observed data, we could 146 estimate the distribution of efficacies across the population of 147 ships. In so doing, we simultaneously used information across 148 ships to inform the likely values for each ship. For instance, if we 149 found no propagules across many ships, we would be more 150 certain that the underlying density was close to zero than if we 151 had treated each ship in isolation. 152

We first estimated the density of Great Lakes' zooplankton in a 153 given tank, both before (λ_b) and after (λ_e) BWE, assuming data 154 from three subsamples at each time period was the result of 155 random sampling and a Poisson distribution of organisms. 156 Efficacy was then derived for each of four vessel trips: 157

$$(E = \lambda_{\rm e}/\lambda_{\rm b}) \tag{1}$$

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

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

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

$$pdf(E_{b} \mid \alpha, \beta) = \frac{1}{B(\alpha, \beta)} E_{b}^{\alpha - 1} (1 - E_{b})^{\beta - 1}$$
(4)

where *L* is the likelihood obtained from pmf/pdf (eqs 3 and 4), pr 161 is the probability, N is the vector of observations of number of 162 organisms from all ships, before and after BWE, and λ is the 163 vector of true densities (eq 2). α and β are shape parameters that 164 define the beta distribution, which will determine the population 165 distribution of λ across ships, based on the data. We converted 166 λ into proportion E (comparing before and after BWE within 167 each ship), so that we could use the beta distribution to 168 determine exchange efficiencies across ships. Specifically, for 169



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.

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The modeled efficacy of BWE between freshwater ports, based 176 on observed plankton densities, was remarkably high. The 177 average proportion of individuals expected to be lost across all 178 ships as a result of the combined effects of physical purging and 179 osmotic stress ranged from 99.988% to 99.997%, with a mode of 180 99.993% (Figure 1). The cumulative evidence from the above F1 181 cause and effect studies indicates that the prescribed manage-182 ment practices of BWE or flushing can effectively decrease 183 propagule pressure in freshwater ballast. 184

2. Is BWE/Flushing Effective under Operational Conditions? 185 To determine if BWE and flushing remain effective when imple-186 mented without highly controlled conditions, we opportunistically 187 sampled 19 NOBOB tanks on 15 vessels, and 24 ballasted tanks on 188 16 vessels from transoceanic and coastal ships arriving to the Great 189 Lakes between November 2005 and May 2008. NOBOB tanks were 190 sampled by filtering 50 L residual water through a 53 μ m mesh 191 plankton net; sampling methodology was similar to that of an earlier 192 study,²⁶ allowing comparison of results before and after introduction 193 of flushing regulations. Ballasted tanks were typically sampled by 194 lowering a plankton net into full tanks, such that at least 1000 L of 195 water was filtered for analysis; methodology was similar to that of 196 earlier studies,^{27,28} allowing comparison of results before and after 197 introduction of BWE regulations. 198

We explored differences in taxonomic composition of samples 199 200 for NOBOB and ballasted tanks separately. For all analyses, plankton densities were averaged for tanks within ships, since 201 these cannot be considered independent samples.²⁹ Following 202 Duggan et al.,²⁶ we recognize that measures of total invertebrate 203 abundance may overestimate effective invasion risk, thus we 204 conducted additional comparisons using only "high risk" species. 205 Species were defined as high risk for establishment in the Great 206 Lakes if any global population of the taxon was previously 207 recorded from fresh or brackish waters, which we conservatively 208 209 defined as salinities of $\leq 18\%$, and included all taxa sampled from 210 tanks containing fresh or brackish water by default. Analyses were 211 conducted using a Mann-Whitney U-test since data could not be transformed to meet assumptions of parametric tests. A 212 significance level of 0.05 was utilized for all analyses; all statistical 213



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 Services²⁷ 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 217 abundance of all invertebrates (range 0.0 to 5440.0 ind \cdot m⁻³; 218 median 60.0 ind. m^{-3}) and of high risk invertebrates (range 0.0 to 426.7 ind $\cdot m^{-3}$; median 0.0 ind $\cdot m^{-3}$) sampled from residual 219 220 ballast water after flushing regulations were in place were sig-221 nificantly 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 224 identified to species level have been recorded in brackish waters 225 including Acartia nr. clausi, Paracalanus parvus, Pseudocalanus 226 minutus, and Oithona similis (Supporting Information (SI) 227 Appendix S1). Salinity of residual water from which these taxa 228 were sampled exceeded 30% in four of six cases, indicative of 229 successful tank flushing in the open ocean. Similarly, total abun-230 dance of invertebrates collected from ballasted tanks ranged from 231 40.0 to 26220.0 ind \cdot m⁻³ (median 2672.9 ind \cdot m⁻³), while that of 232

Table	1. 9	Summary	Statistics	of Ballas	t Water	Salinity,	By Tan	k, As	Measured	during	Ballas	t Tanl	k Exams	in 2005-2	2007 "
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		2	005			2	006			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 (\geq 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 ba	llast whe	ereas ball	asted tan	ks carry	large volu	imes of F	allast w	ater ^b "Di	v" tanks	from wh	nich no w	ater was		

retrieved, were excluded from analysis.

high risk invertebrates ranged from 0.0 to 280.5 ind. m^{-3} (median 233 1.0 ind \cdot m⁻³). Comparison with preregulation studies indicates 234 that mean and maximum density of invertebrates in ballasted tanks 235 have been reduced, particularly for high risk taxa, although median 236 density has not changed significantly (Mann–Whitney U test, *p* = 237 0.060 and p = 0.70 for all and high risk taxa, respectively; Figure 2c, 238 d). Two freshwater taxa (Daphnia spp., and Diaphanosoma sp.) 239 and five species recorded from brackish water (Acartia tonsa, 240 Amphiascus sp., Eurytemora hirudinoides, Pseudodiaptomus corona-241 tus, and Crangon septemspinosa) were observed, typically at very 242 low abundance and occurrence (SI Appendix S1). 243

Considering the median density of high risk taxa recorded after 244 BWE and flushing, the effective invasion risk for freshwater ports 245 may frequently be equivalent to that expected with ballast water 246 discharge standards developed by the International Maritime 247 Organization (less than 10 individuals \cdot m⁻³ for all organisms greater 248 than 50 μ m in minimum dimension).³⁰ Although maximum 249 densities can be an order of magnitude greater than the international 250 standard, the dramatic decreases in the probability of a single 251 introduction event with extremely high plankton density may be 252 highly relevant, since rare high-density introduction events are 253 thought to be extremely important for new invasions.³¹ Further, 254 the cumulative propagule pressure over time likely has also 255 decreased, resulting in further reduction of invasion risk. Reduced 256 propagule pressure should decrease invasion success, however, there 257 exists an urgent need to determine if a critical threshold population 258 density exists below which invasions fail. Allee effects can be 259 pronounced when populations are founded by few colonizers,³² 260 though this effect might be offset if the colonizers are capable of 261 parthenogenetic reproduction.³³ 262

3. Do Most Vessels Comply with BWE/Flushing Regula-263 tions? To determine if the general vessel population complies 264 with ballast water management regulations, we analyzed data 265 from ballast water reporting forms and ballast tank exam forms 266 collected under the joint inspection program during 2005-2007, 267 inclusive. Reporting forms provided self-reported data on ballast 268 history for individual vessel transits, while tank exam forms 269 provided measurements of ballast water salinity and volume, as 270 measured by Inspectors; salinity measurements $\geq 30\%$ were 271 272 compliant with ballast water management regulations. Ballast 273 tank exams conducted by U.S. Inspectors prior to 2005, and independent of the joint program in 2005-2007, comprised an 274 important contribution to Great Lakes' inspection efforts; how-275 ever, because the proportion of tanks inspected was much more 276



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 281 a ship-wise basis prior to June 2006 and on a tank-wise basis 282 thereafter. For ship-wise analysis, vessels were classified following 283 definitions used by Transport Canada, wherein ballasted vessels 284 carried \geq 200 tonnes of ballast water and/or had at least one main 285

tank containing $\geq 10\%$ of its ballast water capacity, whereas 286 2.87 NOBOB vessels carried <200 tonnes of ballast water and had no main tank containing $\geq 10\%$ of its ballast capacity. The propor-288 tion of transoceanic and coastal vessels given physical ballast tank 289 exams increased from 66% in 2005, to 87% in 2006 and 2007, 2.90 although only 602 reports were recovered for this analysis (56% 291 292 of all joint tank exams; 45% of the vessel population) (SI 293 Appendix S2). Examination of ballast volumes indicates that 294 the median volume of residual ballast water carried by NOBOB vessels was 24 tonnes per ship, or 1.4 tonnes per tank, with a 295 small proportion of vessels (3-16%) having at least one auxiliary 296 tank in ballast (SI Appendix S3). Similarly, ballasted vessels do 2.97 not arrive to the Great Lakes fully loaded with ballast water, but 298 tend to have less than 25% of tanks in ballast (SI Appendix S3). 299

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The number of vessels with all tanks compliant increased steadily 300 over time coincident with the implementation of education and inspection programs (Table 1; Figure 3). The proportion of tanks on F3 302 NOBOB vessels containing euhaline (\geq 30‰ salinity) ballast water 303 increased from 73% in 2005 to 94% in 2007. The sharpest increase in 304 305 residual ballast salinity coincided with the introduction of voluntary NOBOB management practices in August 2005 (Figure 3a). The 306 number of "dry" tanks, from which no water was retrieved to measure 307 salinity, decreased from nearly 60% of all tanks inspected in 2005 to 308 33% in 2007 (SI Appendix S2). This decrease may reflect increased 309 ballast management activities since tanks managed in the mid-310 Atlantic prior to Great Lakes entry should not be subject to the 311 high rates of evaporation common in warmer climates. Dry ballast 312 tanks may indicate that tank flushing did not occur prior to entry, 313 although vessels equipped with stripping systems may remove 314 virtually all ballast from tanks. Therefore, the ability of vessels to 315 physically strip tanks dry should be evaluated and/or physical tank 316 entry during inspection may be warranted to determine risk if salinity 317 318 cannot be measured from the vessel's deck. Given that the proportion of tanks on ballasted vessels with euhaline ballast water increased 319 from 68% in 2005 to 97% in 2007, coincident with a change in 320 inspection effort but not regulatory change, it appears that the level of 321 enforcement of regulations is closely linked to compliance (Table 1; 322 Figure 3b).³⁴ 323

We used tank exam data to determine the level of inspection 324 effort required to detect a single noncompliant tank on a vessel, 325 with 95% confidence, using the probability model: 326

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

where *s* is the number of sampled tanks, *n* is the number of tanks 327 on a vessel, *a* is the number of tanks noncompliant, and *P* is the 328 probability of detecting at least one tank given the sampling effort 329 applied. Approximately half of all tanks containing noncompliant 330 ballast water were the result of incomplete management, where 331 exchange or flushing was conducted but the required 30% 332 salinity was not achieved. Noncompliant vessels typically con-333 tained only one or two tanks in violation. As a result, 20 of 21 334 tanks must be inspected to detect a single noncompliant tank, or 335 336 16 of 21 tanks if two noncompliant tanks are present, to have 95% confidence in results of the inspection program. Conversely, if 337 only one or two tanks are inspected per vessel, there is a 90-95% 338 chance that noncompliant tanks will be missed. 339

340 4. Has Invasion Rate of NIS Declined in the Great Lakes? 341 Ideally, implementation of an environmental policy will be followed by improvement(s) in environmental condition. With 342 respect to biological invasions, the relevant outcome would be a 343



Figure 4. (a) Cumulative number and (b) annual number of shipmediated 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, require 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 367 from the Great Lakes after 1959 (Figure 4a). The rate of aquatic NIS 368 F4 discovery was relatively linear between 1959 and the mid-1980s, 369 after which time it began to increase. The peak number of 370 discoveries occurred in 1992 when six NIS were reported, including 371 five parasitic species associated with the Eurasion ruffe (Figure 4b); 372 the discovery rate begins to decline rapidly after the peak. Segmen-373 ted regression identified 1991 as the most significant change point, 374 which appears to correspond with the date that discovery rate began 375

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to increase. Post-1991, 1995 was identified as the most likely point 376 377 of decline in discovery rate. This inflection point may correspond with a six year time lag after the inception of voluntary ballast water 378 management in 1989, or a two year time lag after implementation of 379 mandatory BWE regulations. Since 2000, shipping activities have 380 been responsible for three of eight (37.5%) aquatic NIS introduc-381 382 tions and no new species have been reported since 2006; this is the 383 first time there has been a four-year gap in ship-mediated aquatic NIS discoveries since 1974-1977, indicating that tank flushing 384 regulations may have been an important addition to the manage-385 ment regime. A third inflection point corresponding with effects of 386 tank flushing regulations may exist; however, several more years of 387 data are required to identify any such point with confidence. 388

DISCUSSION

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Implementation of environmental policies should include an 390 391 assessment to gauge efficacy of changes made to human behavior to ensure management resources are used most effectively. Our 392 comprehensive assessment of the Great Lakes' ballast water 393 management program, using four lines of evidence, indicates 394 that the risk of ship-mediated aquatic NIS introductions has been 395 markedly reduced. First, comprehensive laboratory and ship-396 board studies indicate that BWE and tank flushing can effectively 397 decrease the number of viable propagules in ballast tanks. 398 Modeling indicates that the combined effects of tank purging 399 and osmotic shock are typically 99.993% effective at removing or 400 exterminating freshwater zooplankton. Second, biological mon-401 itoring data confirms that at the operational level, BWE and 402 flushing significantly reduce the probability for rare, high density, 403 404 introduction events and nearly eliminate high risk taxa. Third, compliance rates by the general vessel population appear very 405 high, perhaps a direct result of the intensive inspection regime. 406 Only 4.2% of \sim 2850 tanks tested in 2007 contained ballast water 407 with a salinity <30‰ and, because they were detected by 408 inspectors, were prohibited from being discharged into the Great 409 Lakes. Our analysis indicates that these noncompliant tanks 410 would not be detected at lower inspection effort levels, thus it 411 is very important to maintain intensive inspection efforts to 412 retain confidence in this management regime. Finally, examina-413 tion of the discovery rate of aquatic NIS in the Great Lakes basin 414 supports a decline in ship-mediated introductions following the 415 initiation of the ballast water management program. 416

We acknowledge that ballast water can transport a variety of 417 active and dormant taxa, ranging from microbes and bacteria to 418 fishes and large sessile invertebrates.³⁷⁻³⁹ A complementary 419 study examining efficacy of tank flushing on dormant inverte-420 brate eggs in ballast sediments under operational conditions 421 found significant reductions in total egg density, viable egg 422 density, and density of eggs of high risk NIS.⁴⁰ Unfortunately, 423 a dearth of data precludes assessment of the Great Lakes ballast 424 water management regulations with respect to other taxa. Even 425 so, it is clear that the prescribed management strategies will not 42.6 provide complete protection against aquatic invasions, since a 427 large percentage reduction can still result in substantial propagule 428 pressure if initial densities were high. Total propagule pressure, 429 however, is not reflective of the effective invasion risk for Great 430 431 Lakes ports, since many marine taxa will not be able to survive if 432 introduced into fresh water. Considering that the median density of high risk taxa recorded after BWE and flushing is 0.0 to 1.0 433 ind \cdot m⁻³, the effective invasion risk for freshwater ports may 434 frequently approximate the same level of protection expected 435

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under the ballast water discharge standards developed by the 436 International Maritime Organization.³¹ As ballast water treat-437 ment systems utilizing technologies such as ozonation, chlorina-438 tion and/or filtration are not expected to be implemented on all 439 vessels until 2016, similar ballast water management programs 440 could be implemented immediately around the world to protect 441 the biodiversity of the many freshwater ecosystems which receive 442 ballast water discharges by international vessels (e.g., Antwerp, 443 Rotterdam, Constanta, Gdansk, St. Petersburg). 444

The St. Lawrence River provides an ideal "choke-point" for 445 entry to the Great Lakes from which inspection stations can and 446 do operate to the benefit of the entire basin. While ballast salinity 447 is the main indicator used to enforce ballast regulations, it is not 448 foolproof, as many coastal ports have salinity levels that are 449 indistinguishable from that of ocean water. Secure, geo-refer-450 enced and automated reporting of ballast water exchange loca-451 tions for each tank could eliminate uncertainty of ballast 452 management history, while reducing inspection costs and ship 453 delays.¹² Although inspection programs can be expensive, the 454 cost of inaction is likely far higher: while Transport Canada alone 455 spends \$1.6 million annually for ship inspections, costs of aquatic 456 NIS in the Great Lakes amount to at least \$200 million per year.⁴¹ 457 Changes to environmental policy should be enacted in concert 458 with tools to inspect and enforce regulations or there will be little 459 opportunity to measure, or to expect, program success. The 460 framework of questions outlined in this analysis could be 461 extended to evaluate efficacy of numerous other environmental 462 policies that mandate changes in operational practices, such as 463 requirements for wastewater treatment systems or industrial 464 exhaust scrubbers to reduce point-source pollution, by directly 465 assessing cause and effect of the prescribed technologies, com-466 pliance rates, and changes in the environment. 467

ASSOCIATED CONTENT

Supporting Information. A list of taxa identified during 469 biological sampling, data on inspection rates, and ballast water 470 volume of inspected vessels are available online (Appendices S1, 471 S2, and S3, respectively.) The authors are solely responsible for 472 the content and functionality of these materials. Queries (other 473 than absence of the material) should be directed to the corre-474 sponding author. This material is available free of charge via the 475 Internet at http://pubs.acs.org. 476

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ACKNOWLEDGMENT

We acknowledge efforts of Transport Canada, USCG, 481 SLSDC, and SLSMC Inspectors, and thank program managers 482 for providing data and insight. S. Santavy, L. Quiring, and C. van 483 Overdijk assisted with sample collection of ballasted vessels and 484 anonymous reviewers provided constructive comments that 485 improved this manuscript. BMT Fleet Technology Ltd. collected 486 NOBOB samples, and Biologica Environmental Services Ltd. 487 conducted taxonomic analyses. Funding from Fisheries and 488 Oceans Canada, Transport Canada, the NSERC Canadian 489 Aquatic Invasive Species Network (CAISN), and NSERC 490 Discovery Grants (SAB, BL, HJM) is gratefully acknowledged. 491

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