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EVALUATING AN INVASIVE SPECIES POLICY: BALLAST WATER EXCHANGE IN THE GREAT LAKES

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Abstract. Improvements in environmental policy require an accurate diagnosis of the shortcomings of existing policy. We develop a model for assessing the efficacy of policy instruments aimed at reducing the introduction of nonindigenous species. The model identifies and accounts for several features of the nonindigenous species introduction-detection process that complicate interpretations of monitoring data. Specifically, the model includes explicit attention to the pathway of introduction, a probabilistic description of species detection, and the possibility of attenuation of species introductions over time. We apply this theoretical model to the case of mid-ocean ballast water exchange, which was implemented by the United States in 1990 for the North American Great Lakes. Contrary to other authors who take the recent increase in discoveries of nonindigeneous species (NIS) in the Great Lakes as evidence that ballast water exchange is ineffective, we find that the observed detection record could just as plausibly be explained by a lag of a few years between introduction and detection, even if ballast water exchange was 100% effective. Model results suggest that, under current monitoring regimes, several more years of data would be required to make a conclusive evaluation of ballast water exchange. Better estimation of the lag time between introduction and detection, and a shortening of that lag time with better monitoring, would allow more precise and timely evaluation of the efficacy of ballast water exchange and other policy instruments.

Key words: ballast water; environmental policy; invasive species; maximum likelihood; NIS; nonindigenous species.

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Introduction

Invasions by nonindigenous species are a leading environmental problem (Sala et al. 2000). Intentional and unintentional introductions of nonindigenous species are therefore subject to considerable environmental policy and regulation (Miller and Fabian 2004). One introduction pathway under especially severe scrutiny is ballast water carried by transoceanic vessels (National Research Council 1996, Grigorovich et al. 2003, Endresen et al. 2004, Kerr et al. 2005). The *International Convention for the Control and Management of Ships Ballast Water & Sediments* and the U.S. *National Aquatic Invasive Species Act* are examples of legislation aimed at ameliorating future damage from invasive species, but at a substantial cost to society (Tjallingii 2001). While rare, assessments of the effectiveness of attempts to reduce nonindigenous species (NIS) and the consequent economic impacts arising from policies like these are crucial for evaluating the efficiency of current approaches to environmental management and for identifying strategies to improve policy responses. Introductions of nonindigenous species by ships have resulted in the establishment of at least 24 animal species in the North American Great Lakes since 1959 (Holeck et al. 2004). The Great Lakes support numerous ecosystem services which have been or are likely to be disrupted by future invasions (Lodge 2001). The United States has required ships entering the St. Lawrence Seaway with declarable ballast water on board to have exchanged that water in the ocean prior to discharge within the Great Lakes since 1993 (Locke et al. 1993), Canada and the United States instituted voluntary exchange in 1989 and 1990, respectively. Presently, mid-ocean ballast water exchange (BWE) is conceived as a stopgap measure while alternative technologies for managing ballast water are being studied (Endresen et al. 2004, Drake et al. 2005*b*). Although a few studies have examined the effects of BWE on the viability of biological propagules (Locke et al. 1991, 1993, Drake et al. 2002, Bailey et al. 2006), it is not known if BWE has been effective at reducing invasion rates in the Great Lakes. In fact, because the rate at which new nonindigenous species have been discovered since 1993 is greater than the detection rate prior to 1993, some analysts suggest that ballast water exchange has been ineffective at reducing the introduction rate of species (Grigorovich et al. 2003, Holeck et al. 2004, 2005), although whether the analysis is sufficient to reach this conclusion has

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been challenged (Drake et al. 2005*a*). Therefore, accurately estimating the effectiveness of ballast water exchange is an important goal.

Estimating the effectiveness of BWE—or any other policy for reducing the rate of species invasions—is complicated by a time lag, induced by the combination of population growth and incomplete sampling, between when a species is introduced and when it is discovered (Costello and Solow 2003). Here, we use a model for the combined invasion–detection process to estimate the effectiveness of BWE and to test the hypothesis that BWE has been ineffective. We also test the hypothesis that it has been completely effective, but that an insufficient period of time has passed since regulations were passed in 1993 to detect this effect. We adapt the time-based model of species invasions introduced by Solow and Costello (2004) in their study of invasions in San Francisco Bay to account for ship-vectored species introductions. Our new approach explicitly recognizes ship traffic (rather than time) as the conduit for species arrivals. If ship traffic was constant over time the two approaches would yield identical results. But because traffic has been highly variable over the data record this approach more accurately captures inter-annual variation in species arrivals. Importantly, as in Solow and Costello (2004), the probabilistic lag between introduction and detection is a function only of time and is independent of ship traffic.

Methods

Data

Holeck et al. (2004) compiled a comprehensive list of nonindigenous animals discovered in the Great Lakes, their date of detection, and their probable pathways of introduction. As our concern is primarily with the effectiveness of BWE, we removed all introductions known or believed to have occurred by some means other than the discharge of ballast water (*Alosa aestivalis*, *Alosa chrysoclorisa*, *Cyclops strenuous*, *Daphnia lumholtzi*, *Lepisosteus platostomus*, *Notropis buchanani*, *Scardinius erythrophthalmus*, and *Skistodiaptomus pallidus*). Reasoning that the number of species introduced and established in a given year is related to the volume of shipping activity, we obtained estimates of the number of ships entering the Great Lakes for each year (Holeck et al. 2004; Appendix A) to use in the model of species introductions and discoveries.

Model

To rigorously examine the coupled introduction–detection process of NIS, we developed the following model that captures ship traffic as a vector of introductions, and includes a probabilistic post-introduction detection process. Time lags between introduction and detection, which are a common feature of biological invasions (Kowarik 1995, Crooks 2005), could lead to spurious inferences about rates of species establishment. Our model is general enough to accommodate a wide range of possible introduction and detection processes both pre- and post-BWE. We proceed in two steps. First we develop a modeling framework to represent the introduction process. Then, we develop a framework for the detection process according to which establishment of an introduced species eventually results in detection and entrance into the data record.

Introduction process.—Consistent with the time-scale of our data, we model introductions on an annual basis (i.e., introductions per year). We modify the time-only model of Solow and Costello (2004) to include shipping traffic by year, allowing for an attenuation rate that is a function of cumulative shipping traffic. Attenuation might occur if, for example, the number of species that have not previously been introduced declines as cumulative ship traffic increases, i.e., species available for introduction have already been introduced (Levine and D'Antonio 2003). If $s(t)$ is the number of ships in year t, the number of introductions per ship follows a Poisson process with mean

$$\lambda(t) = be^{-gS(t)} \tag{1}$$

where b is a parameter that is interpreted as the "baseline" number of introductions per 1000 ships, g is a parameter capturing the attenuation of introductions as a function of cumulative shipping volume up to, but not including, year t, then the cumulative number of ships up to year t, $S(t)$ is

$$S(t) = \sum_{\tau=0}^{t-1} s(\tau).$$

To obtain the distribution of introductions in year t we simply scale $\lambda(t)$, multiplying by $s(t)$. It follows that the number of introductions in year t is a Poisson process with mean

$$M(t) = s(t)\lambda(t) = bs(t)e^{-gS(t)}. \tag{2}$$

To include the effect of BWE, we suppose that in some year T a policy is enacted that changes the relationship between shipping traffic and new introductions. In the case of the Great Lakes, we consider the implementation of BWE in 1990. Now, if BWE were perfectly effective, and if water discharged from ballasted vessels was the only ship-vectored medium of introductions, there would be no introduction in 1990 (the year the policy was first in effect) or in any year thereafter: $M(t \geq 1990) = 0$. By contrast, if BWE were completely ineffective then $M(t)$ would follow the same trajectory as it did in all previous years. We therefore adapt the model above to include an additional parameter, ε, which captures the effectiveness of BWE. The resulting model is

$$M(t) = \begin{cases} bs(t)e^{-gS(t)} & t < 1990 \\ (1-\varepsilon)bs(t)e^{-gS(t)} & t \geq 1990. \end{cases} \tag{3}$$

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We need not place any parametric restrictions on ε. Different values of ε have the following interpretations. If $\varepsilon < 0$, the estimated post-policy introduction rate is greater than the pre-policy introduction rate, i.e., the policy has had negative effectiveness or is correlated with a factor that has increased the introduction rate. If $\varepsilon = 0$ the post-policy rate $M(t)$ is simply the continuation of the original introduction process. If $0 < \varepsilon < 1$, BWE has been somewhat effective, and in the limiting case where $\varepsilon = 1$, the post-policy introduction rate of species discharged from ballasted vessels is zero. There is no biological interpretation of $\varepsilon > 1$. Thus, our final introduction model has three parameters that must be estimated from the data: b (baseline number of introductions per 1000 ships), g (attenuation rate of introductions), and ε (effectiveness of BWE). By "introduction," we mean an introduction that results in population establishment.

Detection process.—To represent the effect of a lag between introduction and detection, we use the following simple model. In any time period, t, the probability of observing (not necessarily for the first time) any previously introduced species is p. Then, assuming the chance of encountering the species in each year is independent of finding it in every other year, the probability that a species that was introduced in year u is discovered (for the first time) in year t is:

$$P(u,t) = p(1-p)^{t-u}. \tag{4}$$

This is just a shifted geometric distribution that results from the independence of observations and is the product of the probability of failure up to time t, $(1-p)^{t-u}$, and the probability of finally encountering the species at time t, p (see, e.g., Johnson et al. 1993). Combining this detection sub-model with the introduction model in Eq. 3, we have the following model for new discoveries of introduced species in year t:

$$d(t) = \sum_{u=1}^{t} M(u)P(u,t). \tag{5}$$

Now, $d(t)$ follows a Poisson process. Its log-likelihood function is

$$\ell(\boldsymbol{\psi}|y) = \sum_{t} y(t)\log_e[d(t)] - d(t) \tag{6}$$

where $\boldsymbol{\psi}$ is a vector of parameters (b, g, p, and ε) and $y(t)$ is the number of discoveries in year t. Parameter estimates for the full model were obtained by maximizing Eq. 6 using the NPSOL nonlinear optimization routine (Stanford Business Software, Inc., Palo Alto, California, USA). Following DiCiccio and Efron (1996), statistical inferences are obtained using parametric bootstrap.

Results

The series of nonindigenous discoveries comprised 24 animal species from 1959 to 2000, representing an average rate of detection of about one species per year with the rate apparently increasing recently (Fig. 1a). Given that ship traffic has steadily declined over the same period, from about 1000 ships per year prior to the mid-1980s to about 500 ships per year after the mid-1980s, the detection per ship has increased (slope of curve in Fig. 1b). This information allows us to estimate the number of undiscovered species (Fig. 1c). While growing slightly over time, the estimate remains quite low (approximately one undiscovered species in any given year). Most significantly, the maximum likelihood (ML) estimates from this baseline model (Table 1) suggest that the mean introduction rate (not just the mean detection rate) has also increased over time. The estimated mean introduction rate exceeded 0 (even increased) after 1990, reflecting our point estimate of ε that BWE was counterproductive. In 2000, the estimated introduction rate was approximately 1.4 species per year (Fig. 1d). All panels in Fig. 1 are based on the point estimates of the parameters, and thus do not reflect the considerable uncertainty in our knowledge of the invasion process (Table 1).

The estimated baseline introduction rate of approximately 0.14 species per 1000 ships entering the Great Lakes is statistically different from zero (based on confidence intervals), but has a relatively wide range and could be as high as 5.2 species per 1000 ships (Table 1). No evidence for attenuation existed; rather the negative coefficient on g suggests that the rate of introductions actually increased as ship volume accumulated, though the confidence intervals reveal that the null hypothesis of no attenuation cannot be rejected (see *Discussion*).

Our ML estimate of the annual detection probability is about 66%, with an extremely large interval of 1% to 100%. The point estimate suggests that the mean time to detection is <1 year and that 99% of NIS are discovered within five years of introduction. But the uncertainty in the ML estimate precludes drawing meaningful inferences about lag times from this simple model (i.e., the confidence interval on p translates into a mean lag ranging from 0 to 100 years). We return to this point below.

Ultimately, we are interested in the effectiveness of BWE, measured here with the parameter, ε. We find, consistent with the results of Holeck et al. (2004), a point estimate ($\varepsilon = -0.22$) implying that BWE has been counter-productive. The interpretation of this parameter is that introductions in post-BWE years are 22% greater than in the pre-BWE years. However, the confidence interval on ε ranges from -1.0 (extremely counter-productive) all the way to 1.0 (100% effective). Thus, we fail to reject the null hypothesis that BWE has been 100% effective, but similarly fail to reject the null hypothesis that BWE has been completely ineffective. In short, there are too few data to make a statistically defensible conclusion about the efficacy of BWE either way.

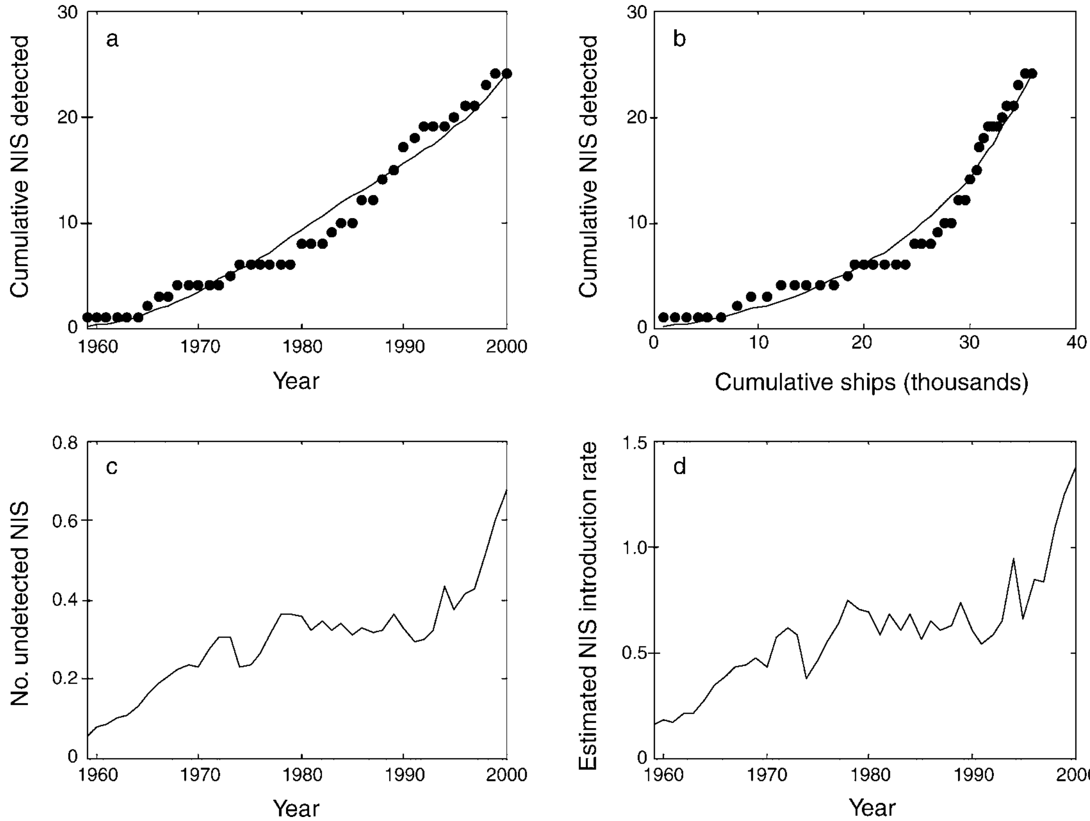

FIG. 1. (a) Cumulative discoveries (dots) and modeled detection process (line) of nonindigenous species (NIS) in the Great Lakes over the period 1959–2000; (b) cumulative discoveries of NIS (dots) and modeled detection process (line) as a function of cumulative shipping traffic; (c) estimated number of undiscovered NIS in each year; and (d) estimated number of NIS introductions each year.

The uncertainty in these results (in particular, the inability to draw inferences about the efficacy of BWE via the parameter ε) stems from the flexibility of the model. Perhaps a more restricted model would allow us to draw more concrete inferences. To test this expectation, we can fix one or more parameters and explore hypothetical situations by maximizing the profile likelihood (Royall 1997). Thus, if we assert a detection probability, p, we can use the model to estimate the remaining three parameters (Table 2). For $p = \{0.02, 0.1, 0.25, 0.5, \text{and } 1.0\}$, corresponding to mean lags of 49, 9, 3, 1, and 0 years (mean lag is $1/p - 1$), we obtain much tighter estimates of model parameters, particularly over the efficacy of BWE, ε (Table 2).

Accordingly, we notice that the smaller the value of detection probability (p), the larger are the estimates not only of the baseline introduction rate, b, but also the effectiveness of BWE, ε. The intuition underlying this is as follows: when p is low, the only way to explain the observed pattern of discoveries is for a large number of species to have arrived (large b), while few have been discovered (small p). Consequently, when b is large, the only way to explain observing only a few species in the post-BWE years is for BWE to have been somewhat effective, which accounts for the larger ε. The point estimate for BWE effectiveness, therefore depends on the detection probability, p. Provided $p \leq 0.25$ (a mean lag of $\geq$3 yr), our point estimate for ε exceeds zero,

TABLE 1. Parameter estimates and bootstrapped confidence intervals for the baseline NIS (nonindigenous species) introduction–detection model.

Parameter	Description	MLE	95% CL
b	baseline introduction rate (per 1000 ships)	0.14	0.02, 5.2
g	attenuation rate (per 1000 ships)	−0.07	−0.15, 0.01
p	annual detection probability	0.66	0.01, 1.0
ε	effectiveness of BWE (% decrease in rate of introductions)	−0.22	−1, 1

Note: BWE is ballast water exchange; MLE is maximum likelihood estimate.

TABLE 2. Parameter estimates and bootstrapped confidence intervals for the introduction model under different assumptions about the annual detection probability, p.

Parameter	MLE	95% CL
$p = 0.02$		
b	1.79	0.21, 6.9
g	0.002	−0.11, 0.14
ε	0.171	−1, 1
$p = 0.10$		
b	0.31	0.05, 0.81
g	−0.05	−0.13, 0.01
ε	0.01	−1, 1
$p = 0.25$		
b	0.17	0.02, 0.47
g	−0.07	−0.16, −0.02
ε	0.01	−1, 0.85
$p = 0.50$		
b	0.14	0.01, 0.39
g	−0.07	−0.16, −0.03
ε	−0.14	−1, 0.70
$p = 1.00$		
b	0.14	0.02, 0.44
g	−0.07	−0.14, −0.02
ε	−0.29	−1, 0.62

Note: Parameters are as defined in Table 1.

which suggests that BWE has been somewhat effective (Table 2). However, the confidence intervals on ε are all large, regardless of p, and all contain 0, implying that we fail to reject the null hypothesis that BWE has been entirely ineffective. Because the lowest estimate of the upper 95% CI is that BWE is 62% effective, we also fail to reject the null hypothesis that BWE has been effective. Importantly, this occurs regardless of the choice of p, so that even if one rejects a priori the idea that lag times are involved in the detection process, there is insufficient evidence to decisively evaluate the effectiveness of BWE.

DISCUSSION

The North American Great Lakes have been invaded by a long series of nonindigenous species, including the 24 animal species on which we focused. In 1990, the United States implemented a voluntary policy of BWE aimed at reducing or eliminating the rate of future invasions, and made BWE mandatory in 1993. Subsequently, a debate has emerged as to whether or not this policy has been effective (e.g., Grigorovich et al. 2003, Holeck et al. 2004, Drake et al. 2005*a*). We believe that assessing effectiveness requires first understanding the invasion process before the policy was implemented, then estimating changes in the invasion rate coinciding with the start of the policy.

We used the time series of first reports of nonindigenous species in the Great Lakes to fit the simplest reasonable model of the pre-policy invasion process. First, we found that the pre-policy invasion rate was not constant, but generally increased over time. Second, when we estimated the effect of policy on the invasion rate we found that the observed post-policy invasion time series is consistent with both a policy that had been somewhat effective and a policy that had been counterproductive. In other words, we conclude that there is not yet enough information to estimate policy effectiveness precisely. In contrast, previous commentators have concluded that BWE has not been sufficiently protective because ship-vectored NIS continue to be discovered even a decade after implementation of the policy. Our analysis demonstrates, however, why these discoveries are not sufficient evidence that the BWE policy has failed.

Indeed, because there is a lag between introduction and detection, we would expect to discover additional nonindigenous species in the post-BWE years, even if BWE was 100% effective. For example, under the assumption that BWE was 100% effective ($\varepsilon = 1.0$), the expected number of new species discoveries, by year, under different assumptions about the detection probability (p) show that only in the highly unlikely circumstance that detection occurs in the same year as introduction ($p = 1.0$) would we expect no new discoveries since 1990 (Fig. 2). Toward the other extreme, if the probability of discovering a species in the year in which it is introduced is as low as 2% (corresponding to a lag time of 50 years), then we would expect to continue to discover species introduced before 1990 far into the future (Fig. 2). What we know is that on the order of five to 10 nonindigenous animal species probably attributable to ballast water release have been discovered since 1990. Given that our 95% confidence interval for our estimate of p ranges from 0.01 to 1.0 (Table 1), we can conclude little other than that we should not be surprised by additional discoveries even if BWE was 100% effective.

On the other hand, these results (Fig. 2) provide a previously missing roadmap for evaluating BWE effectiveness. Provided that $p \leq 0.25$ (lag time $\geq$3 yr), our point estimate is that BWE has been at least somewhat effective (Table 2). If the detection probability (p) can be estimated better in the near future, and especially if p can be both better estimated and increased, it would then become possible to use species detection records to evaluate the effectiveness of BWE (or any other management strategy) in a timeframe that is meaningful to society. On the basis of current knowledge (Fig. 2), it seems likely that many more years of data would be needed to begin to have greater confidence in evaluating BWE with the detection record.

Three aspects of the baseline model warrant further discussion. First, our model depends on an invasion rate represented by the parameter b, which has units of invasions per 1000 ships (maximum likelihood estimate of b is 0.14). Because we fit our model to the total number of ships, rather than only ships declaring to have ballast water on board, we can compare this value to the earlier similarly derived estimate of 0.44 (95% CI

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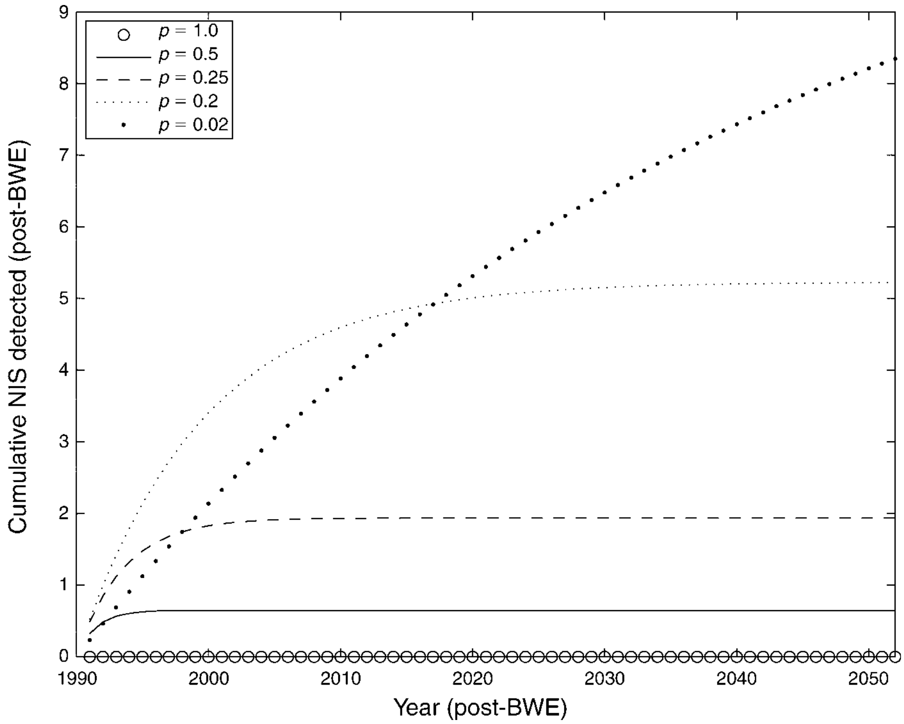

FIG. 2. Projected species discoveries in the post-BWE years assuming ballast water exchange (BWE) was 100% effective, under different assumptions about the annual detection probability, p.

= [0.36, 0.52]) invasions per 1000 ships obtained by Drake and Lodge (2004). The point estimates are consistent to within an order of magnitude and the confidence intervals largely overlapping. It is currently unclear what the relative propagule pressure is from ballasted ships versus ships declaring no ballast on board (NOBOB), which do not exchange water and therefore are unaffected by BWE policy (Niimi and Reid 2003, Drake et al. 2005*c*). We remark that trends in the fraction of ships that are NOBOBs would bias our results by conflating effects due to NOBOBs and effects due to the policy. However, since it is known that the proportion of ballasted vessels declined between 1992 and 2000 (Grigorovich et al. 2003), roughly the period during which ballast water exchange policies were in effect, we could only have overestimated ε.

Second, to account for changes in the rate of species introductions we included an attenuation parameter (g) in the model because it is possible that over time (cumulative shipping) the effective source pool (those species that have not already been introduced) would decline. Contrary to our expectations, the estimated attenuation was negative ($\hat{g} = -0.07$), implying that invasions have been accelerating with respect to ship traffic. Although this was not statistically distinguishable from the null hypothesis of no effect ($g = 0$), we believe that this result is plausible for two reasons. First, over the period of analysis, the size of ships (and the volumes of ballast water) entering the Great Lakes may have increased (although the St. Lawrence Seaway is not navigable by the largest ocean-going vessels). Second, ships have certainly gotten faster so that more species and individuals are likely to survive a transoceanic voyage than in previous decades. Alternative explanations may be equally plausible. In any case, this empirical finding suggests that the need for additional research to understand what factors affect the efficiency with which species are introduced, and how these factors may have changed over time.

Finally, because of year-to-year variation in sampling intensity and heterogeneity in species detectability, our representation of annual detection probability by a single parameter (p) is rather simplistic. However, any more complicated model (e.g., where p is a random variable or has a submodel of its own) would probably be even more flexible. We remark that if there is a positive trend in detection probability, for instance due to increasing interest in invasive species, our model would assign this effect to the policy. Our finding of lags in species detection does not exclude the possibility that species interactions also affect invasion rates (Ricciardi 2001, Holeck et al. 2004). Particularly, the "invasional meltdown" idea implies that average rate at which introduced species establish will increase over time. However, since the introduction process is unobserved, establishment probability and introduction probability are statistically indistinguishable. Clearly, these issues push the limits of our current understanding of the effectiveness of ballast water exchange.

While our analysis here emphasizes the inadequacy of existing detection data to evaluate the efficacy of BWE, we believe that such analysis can be improved and should be considered alongside other relevant information. For example, analysis of live organisms in ballast tanks before and after BWE (Drake et al. 2002), and in residual water and mud in even "empty" ballast tanks (also referred to as no ballast on board tanks) (Duggan et al. 2005) suggests that BWE is not as effective as many expected. Nevertheless, the relationship between organisms in ballast tanks and the probability of establishment is also murky (Wonham et al. 2005), and the most important measure of efficacy is the number of invasions in the ecosystems of concern. We hope that the analyses presented here will prompt better estimation of the factors affecting detection rate, and support more careful use of the detection record in evaluating the efficacy of BWE and other policy efforts aimed at reducing occurrence of nonindigenous species in many ecosystems globally.

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APPENDIX A

Shipping traffic (number of vessels) in the Great Lakes from 1959 to 2000 (*Ecological Archives* A017-027-A1).

APPENDIX B

Nonindigenous animal species in the Great Lakes believed to be introduced through shipping (*Ecological Archives* A017-027-A2).