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ADDITIONAL ANALYSES OF BALLAST WATER MANAGEMENT SCENARIOS TO REDUCE THE ESTABLISHMENT OF HARMFUL AQUATIC SPECIES ACROSS CANADA AND THE GREAT LAKES

Context

The International Maritime Organization's *International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004* (the Convention) establishes global ballast water management regulations for ships to address risks of spreading harmful aquatic organisms and pathogens in ballast water and sediment (IMO 2004). The Convention entered into force in September 2017 and, in turn, parties to the Convention are expected to implement the Convention's ballast water regulations in waters under their jurisdiction. This includes the implementation of a ballast water performance standard (Regulation D-2 of the Convention), which sets limits on the concentration of viable organisms in discharged ballast water. Most ships will adhere to the D-2 standard by using a type approved ballast water treatment system (hereafter referred to as treatment), which utilizes wastewater treatment technologies such as filtration (e.g., screen or disc filters) and disinfection (e.g., ultraviolet radiation, chlorination) processes (Mouawad Consulting 2013). The D-2 standard will replace the currently widespread management method of ballast water exchange (hereafter known as exchange; Regulation D-1), which is the process of discharging ballast water at sea and refilling ballast tanks with oceanic water in an effort to reduce the abundance of high-risk coastal or freshwater organisms. Parties to the Convention also retain the right to impose more stringent requirements for ballast water than those required by the Convention (Art. 2.3; IMO 2004). In 2010, Canada proposed that utilizing exchange plus treatment may provide greater protection against the establishment of harmful species than treatment alone, at least for freshwater ports (IMO 2010).

The Convention applies to international shipping (whether transoceanic or regional), as well as domestic ships that pose a risk to the environment, human health, property and resources. Studies indicate that ballast water moved by Great Lakes ships also introduce nonindigenous species (Briski et al. 2012, Adebayo et al. 2014, Cangelosi et al. 2018). Within the Great Lakes, at least 7 nonindigenous species and 21 indigenous species were transported in ballast water to ports outside of their historical distribution within the region (Briski et al. 2012, Cangelosi et al. 2018). Additionally, Great Lakes ships typically transport a higher organism abundance in ballast water than their transoceanic counterparts because survival is higher on shorter voyages (Rup et al. 2010, Briski et al. 2012, Adebayo et al. 2014). Given that Lakers transport at least 68 million tonnes of ballast water annually and account for 95% of the ballast water moved within the Great Lakes region (Rup et al. 2010), empirical evidence indicates that Lakers play a major role in the dispersal of nonindigenous species within the region.

Canada, a party to the Convention, is currently updating its ballast water management regulations to (i) fulfill its international obligations and (ii) minimize the risk of introducing and spreading harmful aquatic organisms and pathogens through ballast water. Transport Canada's proposed regulations would require ships originating from international waters to use exchange plus treatment to manage ballast water when travelling to Canadian freshwater ports (excluding U.S. transits within the Great Lakes), at least until September 8, 2024 (Canada Gazette 2019). Ships travelling to any other Canadian port would be required to meet the D-2 standard, including domestic ships and Lakers. The proposed regulations are subject to change following the Canadian federal regulatory development process — any modification of details such as timelines and applicability could result in changes to expected efficacy of the regulations.

This study is a follow-up to a previous study (Drake et al. 2020), which used a multi-stage model to estimate the establishment rate of nonindigenous and harmful species in Canada under various ballast water management scenarios, with the objective to determine the effectiveness of exchange plus treatment compared to exchange or treatment alone. Building on the model from Drake et al. (2020), this study estimated the establishment rate for additional ballast water management scenarios, to address the science questions below, following a formal science advice request from Transport Canada:

1. When compared to exchange or treatment, to what extent would requiring ships traveling to Canadian freshwater ports to perform exchange plus treatment reduce the establishment risk of nonindigenous or harmful species in Canada?
2. Relative to the above-mentioned scenario, what is the expected reduction in establishment rate across Canada if exchange plus treatment was only required for ships traveling to either the Great Lakes only or Great Lakes and St. Lawrence River (GLSLR; see Table 1 for details)?
3. To what extent would the utilization of treatment systems on domestic transits within the GLSLR reduce the risk of spreading nonindigenous species among Canadian ports or throughout the entire GLSLR region, and what is the predicted effect on establishment risk if treatment systems are utilized depending on various factors?
4. What is the expected reduction in establishment risk if ballast water is treated using treatment systems on domestic transits across Canada?

Because Great Lakes ships operating binationally between Canada and the U.S. do not undertake ballast water exchange, they are considered along with domestic ships for the purpose of this science advice request.

This Science Response Report results from the Science Response Process of August 10–11, 2020: Additional Analyses of the Effectiveness of Ballast Water Exchange Plus Treatment as a Mechanism to Reduce the Introduction and Establishment of Aquatic Invasive Species in Canadian Ports.

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Analysis and Response

Model Summary

The model from Drake et al. (2020) used to estimate establishment rates of nonindigenous zooplankton and harmful phytoplankton attributed to discharged ballast water includes three main components:

1. Estimating the spatial distribution of shipping activity and the number and relative concentration of species released on each ship transit;
2. Calculating the survival probability of these species based on the environmental correspondence between the ballast source and recipient locations; and,
3. Estimating species establishments based on their initial population size and per-capita establishment probability.

Refer to Drake et al. (2020) for a complete description of the model and input data; methods described below focus on changes to the previous model.

In Drake et al. (2020), environmental distance — which informed species survival probabilities between ballast origin and destination environments — was calculated using three temperature variables (minimum, mean, maximum) and one salinity variable, following Bradie et al. (2015). The four variables were treated equally because the environmental distance model was primarily developed based on marine environments, due to the unavailability of large-scale background data for freshwater environments.

In order to better align our treatment of salinity with its expected biological influence, the model was modified to calculate environmental distance using only the three temperature variables (Figure A1). Salinity was then incorporated by adjusting species' per-capita establishment probabilities (α) depending on the salinity match between the ballast source and the recipient port: α values were unaltered when source and recipient ports had the same salinity type (e.g., marine-marine), were halved when ports had adjacent salinity types (e.g., marine-brackish, brackish-freshwater, or vice versa), and divided by 10 when salinity match was lowest (e.g., marine-freshwater or vice versa). The three salinity categories were defined as fresh ($\leq$ 5.0‰), brackish (5.1–18.0‰), and marine ($\geq$ 18.1‰) as in Drake et al. (2020). As the true change in species' α values due to salinity match is unknown, the adjustments in α were chosen following the rationale that establishment probability would be reduced as the salinity mismatch between source and recipient environments increased (Kinne 1971, Santagata et al. 2008, Ellis and Macisaac 2009, Bradie et al. 2015). This modification combines the survival and establishment steps in the current model since the influence of temperature and salinity has not been quantified for the individual steps.

The current model also included modifications to adjust for changes in efficacy according to the method of performing exchange, where the mean efficacy of exchange was set at 97.9% for empty-refill and 70.1% for flow-through procedures (Ruiz and Smith 2005). While the efficacy of exchange at purging organisms may vary depending on tank design, flow rate, and densities of mixing waters (Ruiz and Smith 2005), these factors were beyond the scope of this study. Therefore, the total organism abundance in a ballast tank was not changed as a result of exchange, instead, the method of exchange dictated the percentage of the source port ballast tank community replaced by the mid-ocean community, with a fraction of the original community retained. The frequency of each exchange method in each Canadian region was estimated from empirical data reported on Canadian Ballast Water Reporting Forms collected by Transport Canada between August 2018–July 2019. The temperature and salinity match assessments were based on the source and recipient port locations for the residual proportion of the ballast community, and the mid-ocean exchange and recipient port locations for the mid-ocean community.

To provide a more realistic modelled effect of treatment, sample organism densities (i.e., total organism concentration) used in the current model for successful and failed treatment were based on data from field studies conducted during 2017–2018, where 32 treated ballast water samples were obtained from international ships arriving to Canadian ports in the Pacific, Atlantic, or GLSLR (Bailey et al. unpublished data). For successful treatments, zooplankton densities were drawn from a Poisson distribution with a mean of 1.58 zooplankton organisms per m^3 and phytoplankton densities were drawn from a truncated gamma distribution with a mean of 1.36 phytoplankton cells per ml. For failed treatments, zooplankton abundances were drawn from a lognormal distribution with a mean of 1,155 individuals per m^3. The post-treatment probability distributions were the best fitting distributions using maximum likelihood. Only post-treatment densities lower than the pre-treatment density could be selected on a voyage, given that an illogical pairing of abundances could be drawn from the probability distributions (e.g., pre-treatment density < post-treatment density). The post-treatment organism abundance distributions were not region--specific (i.e., a single distribution was used for all Canadian regions), due to limited data for treated ballast water samples to date.

Treatment failures for phytoplankton were not observed during 2017–2018 field studies. As the field study sample size was relatively small, it is premature to assume that all treated ballast water will meet the D-2 standard for phytoplankton. Therefore, treatment failures for phytoplankton were simulated by drawing post--treatment organism abundances from a distribution based on rescaling of the zooplankton distribution after failed treatment (a lognormal distribution with a mean of 1,155 cells per ml).

In Drake et al. (2020), the statistical population density of organisms in a ballast tank was estimated based on the sample organism density, since the concentration of organisms in a tank may be slightly higher or lower than that of the sample (see Estimating Species Arrival in Drake et al. 2020 for details). However, in this study, the statistical population density was not calculated for post-treatment sample organism densities, and it was assumed that the post-treatment sample density approximated a well-mixed tank. This is likely to have minimal effect on the model outcome, as the population density is drawn from a normal distribution and there were a large number of ship transits in each simulation.

A new risk metric, the expected number of establishments per year (EPY), was used in this study to account for both primary and secondary introductions of species to Canadian ports. The EPY metric tallied all establishment events regardless of species identity, with the exception that a species may only establish once in each port in a given year. The expected number of unique species per year (SpPY) metric used in Drake et al. (2020), where only the primary establishment event of each species was tallied, was also calculated for comparison purposes (Figures A2). The EPY metric should be considered in conjunction with SpPY since EPY catalogs the establishment of both (i) multiple species at a single port and (ii) a single species at multiple ports. Additionally, since ground-truthing EPY estimations with empirical data is very difficult, the direction and magnitude of change between the management scenarios (rather than numerical values) should be prioritized when interpreting the results (see Model Calibration and Result Standardization in Drake et al. 2020 for details).

Sensitivity Analysis

The sensitivity analysis from Drake et al. (2020) was repeated to examine how establishment rates would change with deviations in the input parameters. To conduct the sensitivity analysis, a 25% increase/decrease was applied to ship traffic volume, mean plankton density (μ), and mean harmful or nonindigenous organisms (β). The pairing of source and recipient ports within each shipping pathway were randomized, and the per-capita establishment probability (α) and Allee effect (c) in the establishment equation were set to 0.005 and 2, respectively.

Modelling the Exchange Plus Treatment Scenarios

The first part of this study compared the efficacy of exchange plus treatment given different possible geographical applications (Table 1). The estimated efficacy for these different permutations were contrasted against baseline scenarios of exchange only and treatment only for all ports. This study used the same biological and shipping data from Drake et al (2020), which included international ship transits destined for Canadian ports in the Pacific, Atlantic, GLSLR, and Arctic from foreign source ports (excluding voyages between U.S. and Canadian Great Lakes ports), and domestic transits destined for Canadian Arctic ports from Canadian source ports in the GLSLR or Atlantic (see Study Area or Shipping and Biological Data Sources in Drake et al. 2020 for details). Only the Arctic domestic pathway was included since exchange can be performed by ships travelling to the Arctic, whereas exchange cannot be performed by Great Lakes ships or ships on domestic transits within or between other Canadian regions. The Canadian ports used in this study are listed in Appendix 2 in Drake et al. (2020); the port salinity data were updated for Little Narrows, NS, from fresh (2.63‰) to brackish (10.28‰) based on new data (Manning et al. 2019). The efficacy of each management scenario was measured as the expected Canada-wide establishment rate for nonindigenous zooplankton or harmful phytoplankton.

Table 1. Exchange plus treatment scenarios examined in this study. All port habitat types (fresh, brackish, and marine) were considered in this study.

Exchange Plus Treatment Scenarios	Description
All ports, exchange	Ballast water exchange for all ports in Canada.
All ports, treatment	Ballast water treatment for all ports in Canada.
Great Lakes, exchange plus treatment; other ports, treatment	Exchange plus treatment for the Great Lakes only, defined as ports upstream of the Saint-Lambert Lock excluding Montreal, QC. Treatment alone for all other ports in Canada.
GLSLR, exchange plus treatment; other ports, treatment	Exchange plus treatment for the Great Lakes-St. Lawrence River (GLSLR) system only, defined as freshwater ports upstream of Île d'Orléans, QC. Treatment alone for all other ports in Canada.
Freshwater ports, exchange plus treatment; other ports, treatment	Exchange plus treatment for all freshwater ports in Canada, including: Kitimat, BC, Stewart, BC, ports on the Fraser River, ports on the Saguenay River, and ports in the GLSLR (TC 2019). Treatment alone for all other ports in Canada.

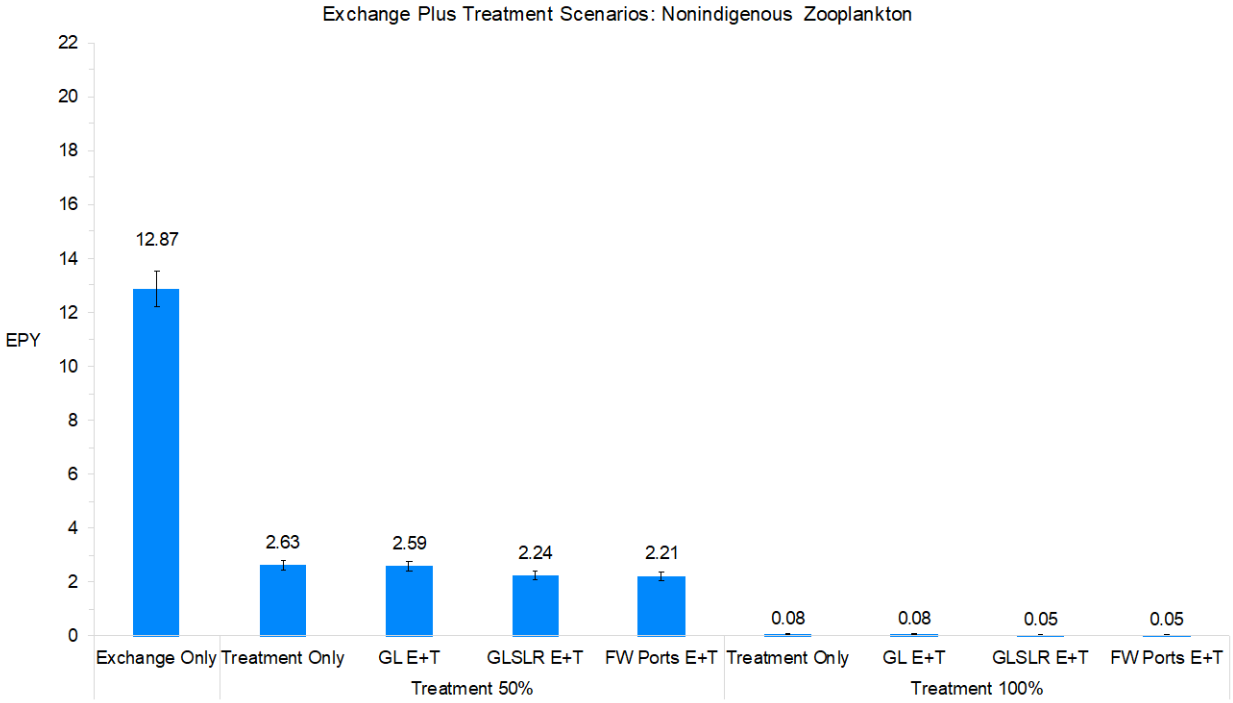
Results of the Exchange Plus Treatment Scenarios

Treatment alone lowered the estimated annual establishment rate of nonindigenous zooplankton from 12.87 (exchange only) to 2.63 EPY, when treatment was effective on half of the transits (Figure 1). Exchange plus treatment for the Great Lakes alone produced a similar reduction in zooplankton establishments (2.59 EPY); these results are likely explained by the very small percentage of transits (1%) which arrived at Great Lakes ports (Table A1). Expanding exchange plus treatment to include freshwater ports on the St. Lawrence River or for all freshwater ports in Canada lowered zooplankton establishments to 2.24 EPY and 2.21 EPY, respectively. Using treatment alone markedly reduced harmful phytoplankton establishments compared to exchange alone, even with 50% treatment efficacy (5.78 EPY vs. 19.88 EPY, respectively; Figure 1), while combining exchange plus treatment had limited effect compared to treatment alone for any of the exchange plus treatment scenarios (ranging from 5.64 EPY to 5.77 EPY).

When treatment is modelled as 100% effective, treatment alone markedly lowered estimated establishments of zooplankton (0.08 EPY) and phytoplankton (0.25 EPY), reducing EPY by > 99% relative to exchange alone (Figure 1). There was therefore limited additional benefit of using exchange plus treatment to reduce nonindigenous zooplankton establishments, particularly for the Great Lakes scenario (EPY of 0.08). Greatest effect was achieved when applying exchange plus treatment to either the GLSLR or all freshwater ports (EPY of 0.05). For phytoplankton, identical establishment rates were produced whether exchange plus treatment was applied to the Great Lakes, GLSLR, or all freshwater ports (0.24 EPY), and these were nearly identical to treatment alone (100% efficacy).

The percentage change values — relative to the exchange only baseline — for the exchange plus treatment scenarios are provided in Table A1. It is important to consider the spatial scale of the scenarios when interpreting both the estimated establishment rates and percentage change values. In this case, the value of interest was the Canada-wide establishment rate, but the effect of exchange plus treatment in freshwater ports may be ‘muted’ by the inclusion of brackish and marine recipient ports that used treatment only. While the utilization of exchange plus treatment for transits arriving to freshwater ports may have a minimal effect on the national establishment rate, the effects are expected to be larger at the regional or port-specific level (DFO 2019a); the national results in this current study do not supersede the regional results from DFO (2019a).

For example, considering establishments within the GLSLR region only, exchange plus treatment (partial efficacy) had 12% greater reduction in SpPY of nonindigenous zooplankton than treatment alone, relative to exchange only (DFO 2019a). However, SpPY reported as a national value, showed a difference of 3% in zooplankton establishments between exchange plus treatment for the GLSLR (all other ports treatment only) and treatment alone for all ports (Table A1).



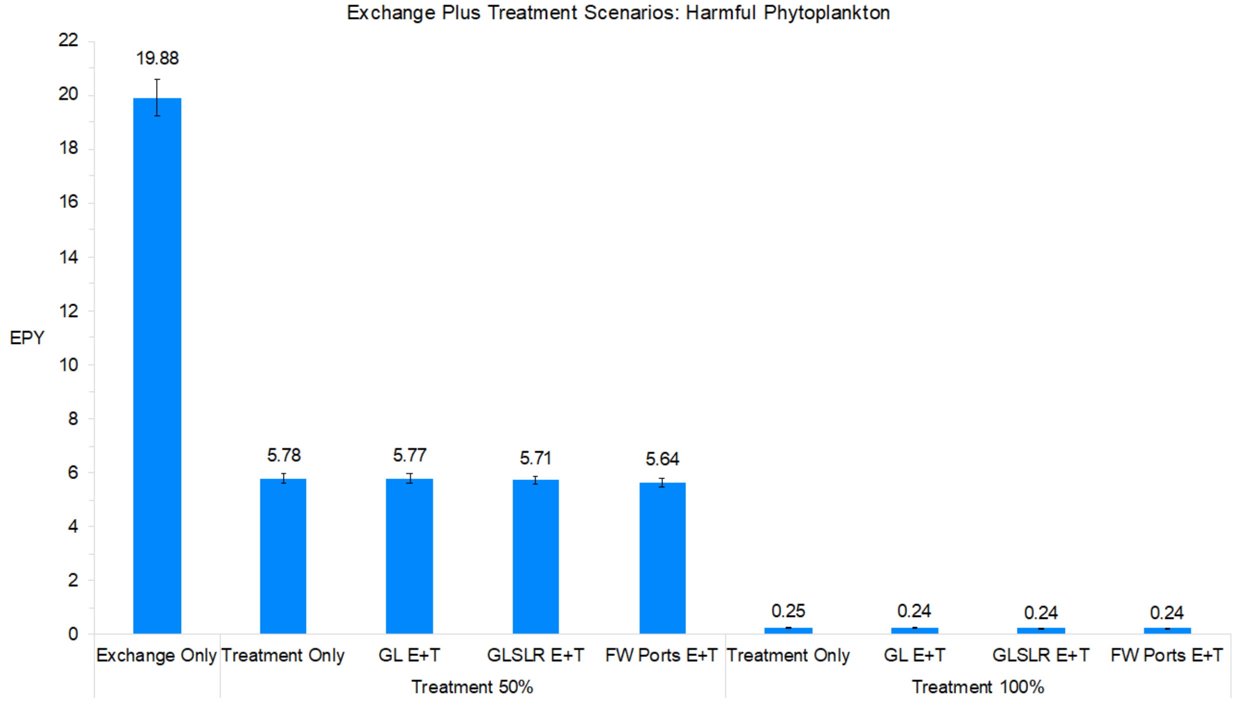


Figure 1. The estimated number of establishments per year (EPY) for nonindigenous zooplankton and harmful phytoplankton across Canada for the exchange plus treatment scenarios. The Great Lakes, Great Lakes-St. Lawrence River and all fresh water ports exchange plus treatment scenarios are denoted by GL, GLSLR, and FW (E+T), respectively. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). Ships were assumed to use treatment alone where ballast water management is not specified. The error bars represent the bootstrapped 95% confidence intervals of the mean of EPY across 1000 iterations.

Modelling the Domestic Shipping Scenarios (Including Great Lakes Ships)

The second part of this study examined various ballast water treatment scenarios for domestic ships, with a focus on different groupings and voyage patterns of Canadian ships and U.S. Lakers within i) Canadian GLSLR waters (Table 2), ii) the entire GLSLR region (Table 3), and iii) Canadian waters in the GLSLR, Atlantic, and Arctic (Table 4). Great Lakes ships were included in these domestic scenarios due to their limited voyage patterns and inability to undertake ballast water exchange. Pacific Canada was not included due to the absence of data for domestic shipping ballast water discharges in the region. Treatment was applied to either 30% or 100% of the Canadian fleet as requested by Transport Canada.

The domestic shipping pathway models used zooplankton data from biological surveys of domestic ballast water in Atlantic Canada and the GLSLR (Briski et al. 2012, DiBacco et al. 2012, Adebayo et al. 2014). The estimated efficacy for each scenario was measured as the expected annual establishment rate of nonindigenous zooplankton. For the species arrival component of the model (see Estimating Species Arrival in Drake et al. 2020 for details), probability distributions were created to characterize (i) the total density of zooplankton in ballast tank samples (Figure A3) and (ii) proportion of nonindigenous zooplankton organisms out of the total population among transits (Figure A4). Zooplankton data were unavailable for the Arctic region, therefore, it was assumed that the concentration and composition of zooplankton on voyages from Arctic source ports were equivalent to those within Atlantic Canada. All nonindigenous zooplankton species identified in the empirical ballast water samples were considered in this study, regardless of their current distribution in the regions of interest.

Shipping data were obtained from Drake et al. (2020) and Casas-Monroy et al. (2014), and the domestic scenarios included both internal and external regional transits where ballast water was transported by ships. Internal transits refer to transits where both the source and recipient ports are within the same geographical region (e.g., GLSLR-GLSLR), while external transits refer to transits where the source and recipient ports are in different geographical regions (e.g., Arctic-GLSLR). As the Arctic domestic pathway was modelled using ship transit data from 2006 and 2015, recent increases in Arctic shipping traffic as a result of increased resource development were not captured in this study.

Table 2. Domestic shipping scenarios relevant to ballast discharges in Canadian GLSLR ports. The scenarios are ordered in increasing application of treatment (each scenario retains the treatment methods from the previous scenarios).

Domestic Shipping Scenarios	Canadian Ships	U.S. Lakers	International Ships
No management	No management	No management	All ships, treatment
30% of Canadian ship trips, treatment	30% of trips, treatment	No management	All ships, treatment
All Canadian ships, treatment	All ships, treatment	No management	All ships, treatment
U.S. Lakers on trips to Canada, treatment	All ships, treatment	U.S. Lakers on trips to Canadian GLSLR ports, treatment	All ships, treatment

Table 3. Domestic shipping scenarios relevant to ballast discharges in both Canadian and U.S. GLSLR ports. The scenarios are ordered in increasing application of treatment (each scenario retains the treatment methods from the previous scenarios).

Domestic Shipping Scenarios	Canadian Ships	U.S. Lakers	International Ships
No management	No management	No management	All ships, treatment
30% of Canadian ship trips, treatment	30% of trips, treatment	No management	All ships, treatment
All Canadian ships, treatment	All ships, treatment	No management	All ships, treatment
U.S. Lakers on trips to Canada, treatment	All ships, treatment	U.S. Lakers on trips to Canadian GLSLR ports, treatment	All ships, treatment
U.S. Lakers on trips from Canada, treatment	All ships, treatment	U.S. Lakers travelling from Canadian GLSLR ports to the U.S., treatment	All ships, treatment
U.S. Lakers visiting Canada at least once in a given year, treatment on all transits	All ships, treatment	U.S. Lakers visiting Canada at least once in a given year, treatment on all transits	All ships, treatment
All ships, treatment	All ships, treatment	All ships, treatment	All ships, treatment

Table 4. Domestic shipping scenarios relevant to ballast discharges in Canadian ports in the GLSLR, Atlantic, and Arctic. The scenarios are ordered in increasing application of treatment (each scenario retains the treatment methods from the previous scenarios). All ports (fresh, brackish, and marine) within the regions of interest were included in this study, and U.S. Lakers only travelled to Great Lakes ports.

Domestic Shipping Scenarios	Canadian Ships	U.S. Lakers	International Ships
No management	No management	No management	All ships, treatment
30% of Canadian Laker trips, treatment	30% of Laker trips, treatment	No management	All ships, treatment
30% of Canadian ship trips, treatment	30% of trips, treatment	No management	All ships, treatment
All Canadian ships, treatment	All ships, treatment	No management	All ships, treatment
U.S. Lakers on trips to Canada, treatment	All ships, treatment	U.S. Lakers on trips to Canadian GLSLR ports, treatment	All ships, treatment

Results of the Domestic Shipping Scenarios

Only EPY values are presented as they best describe the extent of movement of nonindigenous species by domestic shipping. The percentage change values (relative to baseline no management) are provided in Tables A2–A4.

Canadian GLSLR ports

Domestic ships not using any ballast water management resulted in a baseline nonindigenous zooplankton establishment rate of 47.63 EPY in Canadian GLSLR ports (Figure 2).

There was a progressive reduction in establishments for Canadian GLSLR ports as ballast water was treated on more transits. Even when treatment was 50% effective, nonindigenous zooplankton EPY was lowered 23% (36.45 EPY) when treatment was used on 30% of Canadian ship transits (Figure 2 and Table A2). A relatively large decrease (78%) in establishments occurred when all Canadian ships treated their ballast water (10.44 EPY), while the addition of U.S. Lakers treating ballast water discharged in Canada resulted in a reduction of 82% to 8.46 EPY (despite 50% treatment efficacy).

These trends were mirrored, with lower establishment rates, when treatment was 100% successful: nonindigenous zooplankton establishment rates in Canadian GLSLR ports were 33.45 EPY (30% reduction) when 30% of Canadian ship transits applied treatment, 2.71 EPY (94% decrease) for all Canadian ship trips, and 0.35 EPY (99% reduction) for Canadian ships and U.S. Lakers discharging in Canada (Figure 2 and Table A2).

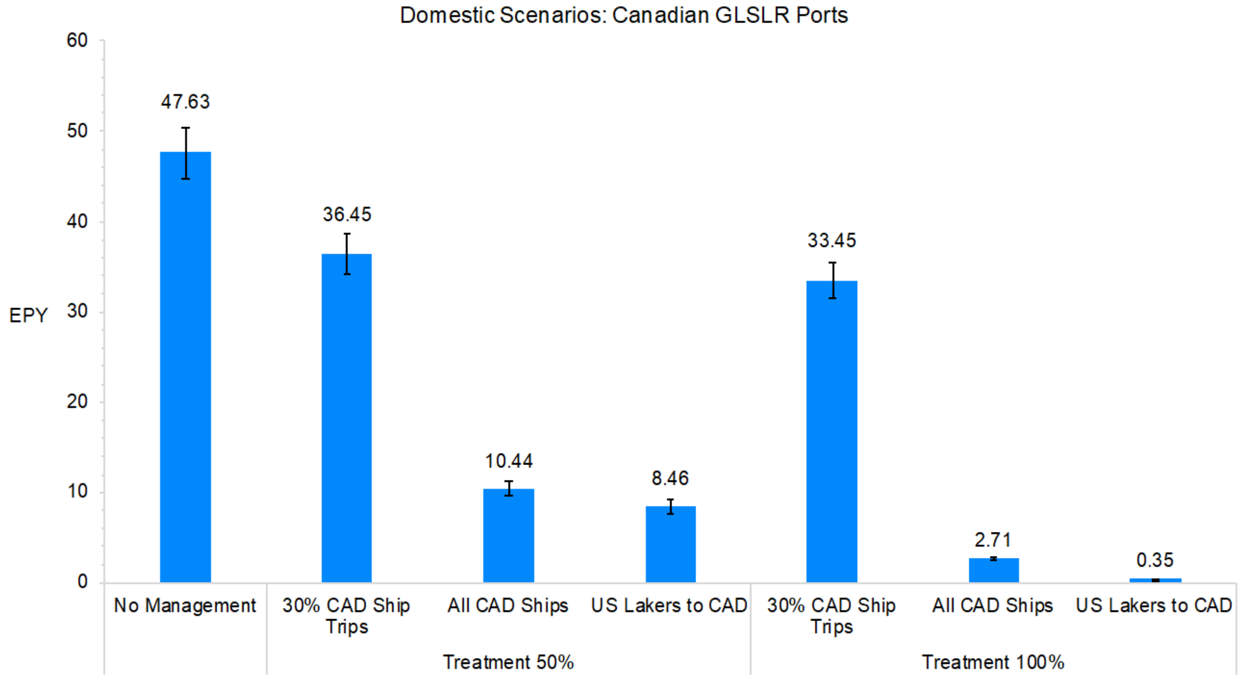


Figure 2. The estimated number of establishments per year (EPY) for nonindigenous zooplankton in Canadian (CAD) GLSLR ports attributed to domestic ballast water discharge. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). The error bars represent the bootstrapped 95% confidence intervals of the mean of EPY across 1000 iterations.

Canadian and U.S. GLSLR ports

Considering the entire GLSLR region (both Canadian and U.S. ports), no management by domestic ships produced a baseline of 152.00 nonindigenous zooplankton EPY (Figure 3).

Utilizing treatment (50% efficacy) on 30% of Canadian ship transits lowered the estimated establishment rate by 11% to 135.14 EPY (Figure 3 and Table A3). Similarly, treatment (50% efficacy) applied to all Canadian ship trips provided a 37% reduction in EPY (95.74 EPY). Adding treatment (50% efficacy) for U.S. Lakers that visited Canada at least once annually produced a decrease in establishments of 71% (44.26 EPY), while treating all domestic ballast water resulted in a reduction of 83% (25.30 EPY).

Fully effective treatment that met D-2 with every application provided greater establishment reductions, with similar trends across scenarios. Treatment on 30% of Canadian ship transits reduced EPY by 14% (131.05 EPY), treatment by the Canadian fleet on all transits produced a 44% decrease in EPY (84.53 EPY), treatment by Canadian ships and U.S. Lakers that visited Canada at least once annually lowered EPY by 85% (23.50 EPY), and treatment by all ships resulted in a 99% decrease in EPY (1.00 EPY; Figure 3 and Table A3).

Within the GLSLR region, treatment on U.S. Laker trips from Canada to the U.S. resulted in incremental reductions in nonindigenous zooplankton EPY of 3% (with 50% treatment efficacy) and 4% (full efficacy; Table A3). This model does not estimate the rate of species spread back to Canada by any vector following their establishment in U.S. ports (see DFO 2019b for review).

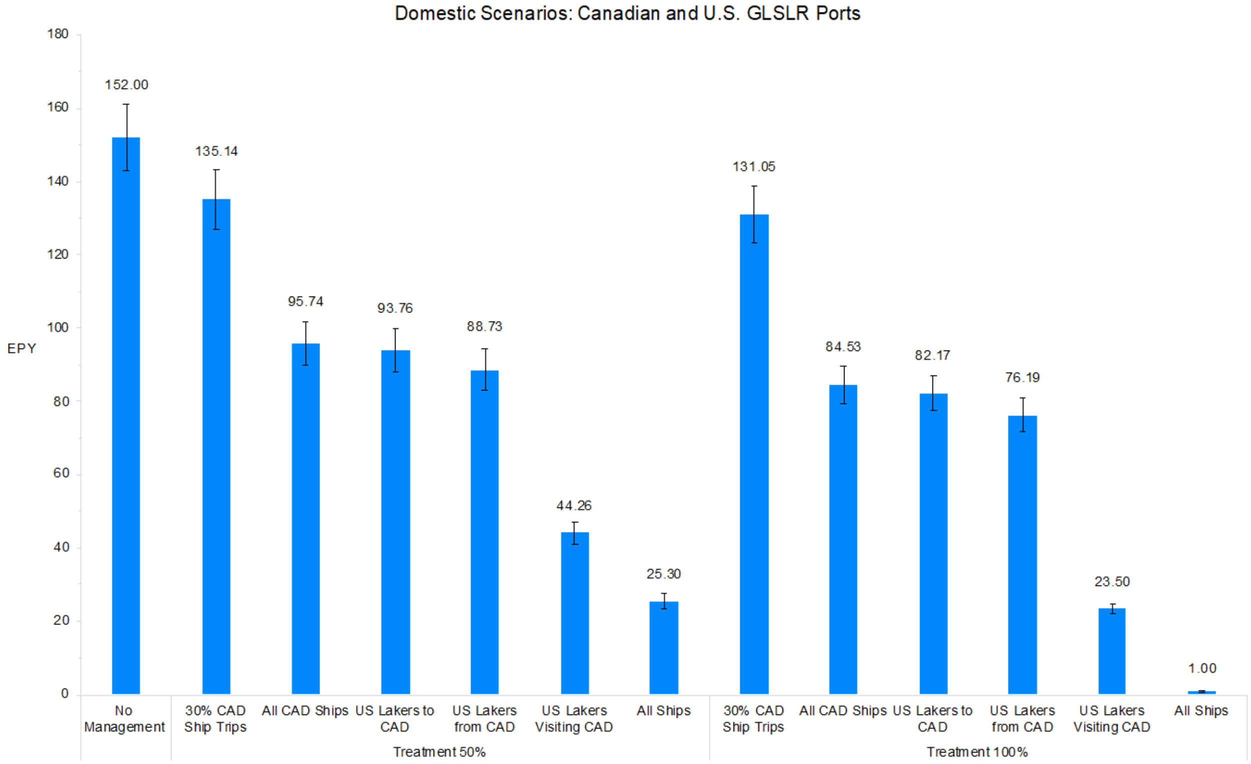


Figure 3. The estimated number of establishments per year (EPY) for nonindigenous zooplankton in both Canadian (CAD) and U.S. GLSLR ports due to domestic ballast water discharge. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). The error bars represent the bootstrapped 95% confidence intervals of the mean of EPY across 1000 iterations.

Canadian ports in the GLSLR, Atlantic, and Arctic

No ballast water management by domestic ships had a baseline nonindigenous zooplankton establishment rate of 52.94 EPY across Canadian ports in the GLSLR, Atlantic, and Arctic (Figure 4).

Treatment with a 50% efficacy rate on 30% of Canadian ship trips reduced nonindigenous zooplankton establishments by 24% (40.22 EPY; Figure 4 and Table A4). Treatment (50% efficacy) on all Canadian ship transits reduced zooplankton establishments by 79% (11.00 EPY), while treating all domestic ballast water discharged in Canada reduced EPY by 83% (9.02 EPY).

The establishment rates were lower when treatment events were 100% successful: treatment on 30% of Canadian ship transits reduced nonindigenous zooplankton establishments by 30% to 36.83 EPY, treatment on Canadian ship trips decreased establishments by 95% to 2.72 EPY, and treatment by the Canadian fleet plus U.S. Lakers had a reduction of 99% to 0.36 EPY (Figure 4 and Table A4). The reduction in zooplankton establishments were similar between treatment on 30% of all Canadian ship transits and 30% of Canadian Laker trips only.

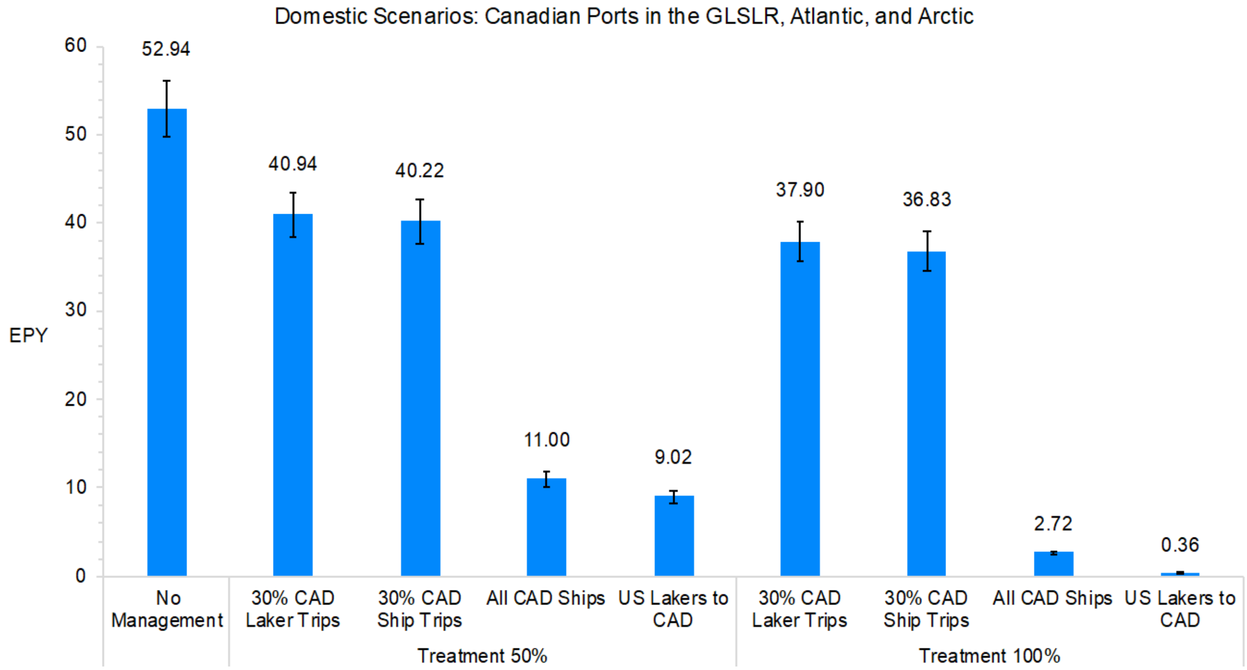


Figure 4. The estimated number of establishments per year (EPY) for nonindigenous zooplankton in Canadian (CAD) ports in the GLSLR, Atlantic, and Arctic attributed to domestic ballast water discharge. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). The error bars represent the bootstrapped 95% confidence intervals of the mean of EPY across 1000 iterations.

Model Sensitivity

The sensitivity analysis was conducted for the same management scenarios as in Drake et al. (2020) with the SpPY metric for comparative purposes (see Table 3 in Drake et al. 2020 for details on the scenarios). The sensitivity analysis would be expected to have the same general effect on the EPY metric, as the relative differences between the scenarios were similar between EPY and SpPY (Table A1).

In general, the results of the sensitivity analysis were similar to that of Drake et al. (2020), demonstrating that changes made to the model for this assessment did not affect its robustness. The sensitivity analysis showed most of the model parameters had < 10% deviation following 25% change in input, indicating an overall low effect on the model’s outcome (Table A5). In some cases, a larger percentage change was observed when SpPY values were small since even small differences can equate to large percentage change values. Large percentage changes in SpPY were also observed when the per-capita establishment probability (α) was set to 0.005 (all species were parthenogenetic), but it may not be realistic to assume all species can reproduce clonally. Additionally, SpPY increased 62% on average when c was changed from 1 (no Allee effect) to 2. In all cases, the relative performance of the management methods remained the same.

Sources of Uncertainty

See Sources of Uncertainty in Drake et al. (2020) for a complete description of the uncertainties in the model, as the following paragraph only discusses the uncertainties associated with the changes to the model.

Species' per-capita establishment probability (α) values were adjusted based on the salinity match between the ballast source and recipient ecosystems, however, the appropriate adjustment in α given environmental salinity is unknown, contributing to uncertainty in the relative effectiveness of exchange.

This study included a measure of the efficacy of exchange at purging organisms from ballast tanks, but the assumption that exchange does not change organism abundances was retained from Drake et al. (2020). A change in organism abundance after exchange was not modelled because of inconsistencies in the occurrence and direction of change and high variability among transits (Ruiz and Smith 2005; see Modelling the Management Scenarios in Drake et al. 2020 for details). Therefore, it was assumed that all residual organisms survived in ballast tanks following exchange, even on transits where the residual community was fresh water. It is acknowledged that the survival of residual organisms in ballast tanks was likely overestimated on certain voyages, as most residual freshwater organisms (and some brackish organisms) would have a lower survival probability in tanks following mid-ocean exchange.

There is uncertainty associated with the inclusion of empirical post-treatment sample densities in simulations of ballast water treatment. First, the simulated post--treatment phytoplankton densities after failed treatments are based on empirical zooplankton counts, as treatment failures for phytoplankton were not observed during field studies. However, zooplankton and phytoplankton have different concentrations inside ballast tanks and treatment may have different effects on these two taxonomic groups. Therefore, the expected harmful phytoplankton establishment rate for the scenarios with failed treatment should be interpreted with greater caution. The phytoplankton results may need to be reassessed if treatment failures occur in future field studies with a markedly different distribution than that used in this study. Second, the pre--treatment and post--treatment sample organism density data were obtained from studies conducted during different time periods, and the post--treatment density data was not region-specific due to limited number of treated ballast water samples available. Although this disconnect between pre--treatment and post--treatment organism densities is not ideal, the severity of the issue is reduced with large sample sizes. Therefore, additional post-treatment density data (and pathway-specific data) could improve the establishment estimates for ballast water treatment.

The model did not consider the species composition at a given recipient port, as species were assigned to transits, rather than ports (see Estimating Species Arrival in Drake et al. 2020 for details). Therefore, the establishment rates generated may count establishment events for species already present at a given port; the overlap of species between the transits and recipient ports is likely to be higher in the domestic pathway compared to the international pathway since the pool of species being transported within Canada and the Great Lakes is more limited than the international pool of species. Potential overlap should be considered to better understand the impact of the modeled establishments.

Lastly, the rare species in ballast water samples may be underestimated, given limitations of identifying species using microscopy techniques. This uncertainty would also apply to Drake et al. (2020).

Conclusions

1) When compared to exchange or treatment, to what extent would requiring ships travelling to Canadian freshwater ports to perform exchange plus treatment reduce the establishment risk of nonindigenous or harmful species in Canada?

Requirements for exchange plus treatment applied to ships travelling to Canadian freshwater ports reduced the EPY of nonindigenous zooplankton by 10.66 EPY compared to exchange only or 0.42 EPY compared to treatment only, when treatment was 50% effective. When treatment was 100% successful, the application of exchange plus treatment to ships travelling to Canadian freshwater ports resulted in 0.03 fewer EPY of nonindigenous zooplankton compared to treatment alone.

Requirements for exchange plus treatment applied to ships travelling to Canadian freshwater ports reduced the EPY of harmful phytoplankton by 14.24 EPY compared to exchange only or 0.14 EPY compared to treatment only, under the 50% treatment success scenario. When all vessels adhered to the D-2 standard, the application of exchange plus treatment to ships travelling to Canadian freshwater ports is not expected to improve the risk reduction offered by treatment alone.

Reporting the establishment rate as a national value ‘muted’ the effect of exchange plus treatment in freshwater ports due to the inclusion of marine and brackish ports that used treatment only. Exchange plus treatment had a larger effect on freshwater ports when establishments were reported on a regional level. For example, within the GLSLR region only, exchange plus treatment lowered the invasion rate of nonindigenous zooplankton an additional 12% compared to treatment alone, when treatment was 50% effective (DFO 2019a). The national results in this study do not supersede the regional model results from DFO (2019a).

2) Relative to the above-mentioned scenario, what is the expected reduction in establishment rate across Canada if exchange plus treatment was only required for ships travelling to either the Great Lakes only or GLSLR?

Relative to the above scenario of ships traveling to any freshwater Canadian port, requiring exchange plus treatment only for the Great Lakes or GLSLR increased the EPY of nonindigenous zooplankton by 0.38 EPY and 0.03 EPY, respectively, when treatment was 50% effective. When treatment was always successful, requiring exchange plus treatment only for the Great Lakes increased the establishment rate for nonindigenous zooplankton by 0.03 EPY, while there was no change for the GLSLR scenario.

For harmful phytoplankton, requiring exchange plus treatment only for the Great Lakes or GLSLR increased the establishment rate by 0.13 and 0.07, respectively, when treatment was 50% effective. When treatment was fully effective, there was no additional benefit for a requirement of exchange plus treatment for any set of ports concerning harmful phytoplankton.

3) To what extent would the utilization of treatment systems on domestic transits within the GLSLR reduce the risk of spreading nonindigenous species among Canadian ports or throughout the entire GLSLR region, and what is the predicted effect on establishment risk if treatment systems are utilized depending on various factors?

In Canadian GLSLR ports, utilizing treatment with a 50% success rate on 30% of Canadian ship transits reduced the nonindigenous zooplankton EPY by 23%, while treating discharges by

Canadian ships lowered EPY by 78%, and treating all discharges produced the greatest reduction in EPY of 82%.

Within the entire GLSLR region (Canadian and U.S. ports), treatment by the full Canadian fleet and U.S. Lakers on trips to or from Canada produced reductions in nonindigenous zooplankton EPY of 42% (with 50% treatment efficacy) and 50% (100% treatment efficacy). Treating all ballast water discharged by Canadian ships and U.S. Lakers reduced nonindigenous zooplankton EPY by 83% (50% treatment efficacy) or 99% (100% treatment efficacy).

4) What is the expected reduction in establishment risk if ballast water is treated using treatment systems on domestic transits across Canada?

Considering Canadian ports in the GLSLR, Atlantic, and Arctic, treatment with 50% efficacy utilized on 30% of Canadian Laker voyages produced a 23% reduction in nonindigenous zooplankton EPY, while treatment by 30% of all Canadian ship voyages reduction EPY by 24%. Treatment (partial efficacy) by the full Canadian fleet produced a 79% reduction in nonindigenous zooplankton EPY, and treatment by Canadian ships and U.S. Lakers resulted in 83% reduction in EPY.

When all treatment events met D-2, using treatment on 30% of Canadian Laker trips reduced nonindigenous zooplankton EPY by 28%, treatment on 30% of Canadian ship trips lowered EPY 30%, treatment on all Canadian ship trips decreased EPY by 95%, and treatment on all domestic transits decreased EPY by 99%.

Contributors

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Sources of Information

This Science Response Report results from the Science Response Process of August 10–11, 2020: Additional Analyses of the Effectiveness of Ballast Water Exchange Plus Treatment as a Mechanism to Reduce the Introduction and Establishment of Aquatic Invasive Species in Canadian Ports.

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Appendix 1. Supplementary Tables

Table A1. Percentage change in the estimated Canada-wide establishments per year (EPY) and species per year (SpPY) relative to exchange only, for the exchange plus treatment scenarios. The Great Lakes, Great Lakes-St. Lawrence River and all fresh water ports exchange plus treatment scenarios are denoted by GL, GLSLR, and FW (E+T), respectively. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). Ships were assumed to use treatment alone where ballast water management is not specified.

	Nonindigenous Zooplankton				Harmful Phytoplankton				
	Treatment 50%		Treatment 100%		Treatment 50%		Treatment 100%		
Management Scenario	EPY	SpPY	EPY	SpPY	EPY	SpPY	EPY	SpPY	Percentage of Trips using E+T
Treatment Only	-78%	-59%	-99%	-97%	-72%	-41%	-99%	-93%	0%
GL E+T	-78%	-59%	-99%	-97%	-72%	-41%	-99%	-93%	1%
GLSLR E+T	-82%	-62%	-100%	-98%	-72%	-41%	-99%	-93%	10%
FW Ports E+T	-82%	-62%	-100%	-98%	-73%	-42%	-99%	-93%	16%

Table A2. Percentage change in the estimated number of establishments per year in Canadian (CAD) GLSLR ports, relative to no management for domestic ships. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%).

	Nonindigenous Zooplankton		
Management Scenario	Treatment 50%	Treatment 100%	Percentage of Trips using Treatment (excluding International Ships)
30% CAD Ship Trips	-23%	-30%	29%
All CAD Ships	-78%	-94%	95%
US Lakers to CAD	-82%	-99%	100%

Table A3. Percentage change in the estimated establishments per year in both Canadian (CAD) and U.S. GLSLR ports, relative to no management for domestic ships. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%).

	Nonindigenous Zooplankton		
Management Scenario	**Treatment 50%**	**Treatment 100%**	**Percentage of Trips using Treatment (excluding International Ships)**
30% CAD Ship Trips	-11%	-14%	9%
All CAD Ships	-37%	-44%	30%
US Lakers to CAD	-38%	-46%	31%
US Lakers from CAD	-42%	-50%	35%
US Lakers Visiting CAD	-71%	-85%	70%
All Ships	-83%	-99%	100%

Table A4. Percentage change in the estimated establishments per year in Canadian (CAD) ports in the GLSLR, Atlantic, and Arctic, relative to no management for domestic ships. The scenarios are ordered in increasing application of treatment and each scenario retains the treatment methods from the previous scenarios. International ships treated their ballast water on all transits, and Canadian ships and U.S. Lakers were assumed to use no ballast water management where treatment is not specified. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%).

	Nonindigenous Zooplankton		
Management Scenario	**Treatment 50%**	**Treatment 100%**	**Percentage of Trips using Treatment (excluding International Ships)**
30% CAD Laker Trips	-23%	-28%	18%
30% CAD Ship Trips	-24%	-30%	29%
All CAD Ships	-79%	-95%	97%
US Lakers to CAD	-83%	-99%	100%

Table A5. Model sensitivity to changes in input parameters. The response variable is the estimated Canada-wide species per year, and the percentage change values are in relation to the null value. The management methods assessed are no management (NM), exchange (E), treatment (T), and exchange plus treatment (E+T). For treatment, either i) half of the treatment events successfully met D-2 (T 50%) or ii) all treatment events successfully met D-2 (T 100%).

				Transit Frequency		Mean Plankton Density μ		Mean Nonindigenous or Harmful β		$\alpha = 0.005$	Allee Effect
Management Scenario		**Null**	**Randomized Port Pairings**	**+25%**	**-25%**	**+25%**	**-25%**	**+25%**	**-25%**	**All Species**	$c = 2$
					Nonindigenous Zooplankton						
-	NM	1.849	1.861	2.004	1.763	2.125	1.729	2.025	1.762	54.626	3.976
		-	1%	8%	-5%	15%	-6%	10%	-5%	2854%	115%
	E	1.872	1.888	1.992	1.741	2.130	1.722	2.023	1.70	54.323	3.917
		-	1%	6%	-7%	14%	-8%	8%	-9%	2802%	109%
T 50%	T	0.796	0.814	0.886	0.733	0.862	0.783	0.866	0.739	22.293	1.778
		-	2%	11%	-8%	8%	-2%	9%	-7%	2701%	123%
	E+T	0.746	0.772	0.810	0.705	0.822	0.792	0.827	0.682	20.827	1.686
		-	3%	9%	-5%	10%	6%	11%	-9%	2692%	126%
T 100%	T	0.060	0.061	0.073	0.060	0.072	0.069	0.081	0.046	0.481	0.049
		-	2%	22%	0%	20%	15%	35%	-23%	702%	-18%
	E+T	0.052	0.055	0.060	0.055	0.057	0.073	0.071	0.031	0.354	0.025
		-	6%	15%	6%	10%	40%	37%	-40%	581%	-52%
					Harmful Phytoplankton						
-	NM	1.450	1.393	1.558	1.356	1.492	1.320	1.589	1.398	41.657	3.001
		-	-4%	7%	-6%	3%	-9%	10%	-4%	2773%	107%
	E	1.488	1.387	1.548	1.361	1.517	1.329	1.618	1.443	41.635	2.942
		-	-7%	4%	-9%	2%	-11%	9%	-3%	2698%	98%
T 50%	T	0.851	0.820	0.932	0.782	0.858	0.819	0.985	0.816	27.139	1.845
		-	-4%	10%	-8%	1%	-4%	16%	-4%	3089%	117%
	E+T	0.852	0.835	0.927	0.805	0.868	0.831	0.995	0.816	27.181	1.809
		-	-2%	9%	-6%	2%	-2%	17%	-4%	3090%	112%
T 100%	T	0.141	0.109	0.138	0.110	0.113	0.132	0.172	0.100	1.116	0.095
		-	-23%	-2%	-22%	-20%	-6%	22%	-29%	691%	-33%
	E+T	0.151	0.118	0.152	0.107	0.117	0.146	0.177	0.119	1.125	0.104
		-	-22%	1%	-29%	-23%	-3%	17%	-21%	645%	-31%

Appendix 2. Supplementary Figures

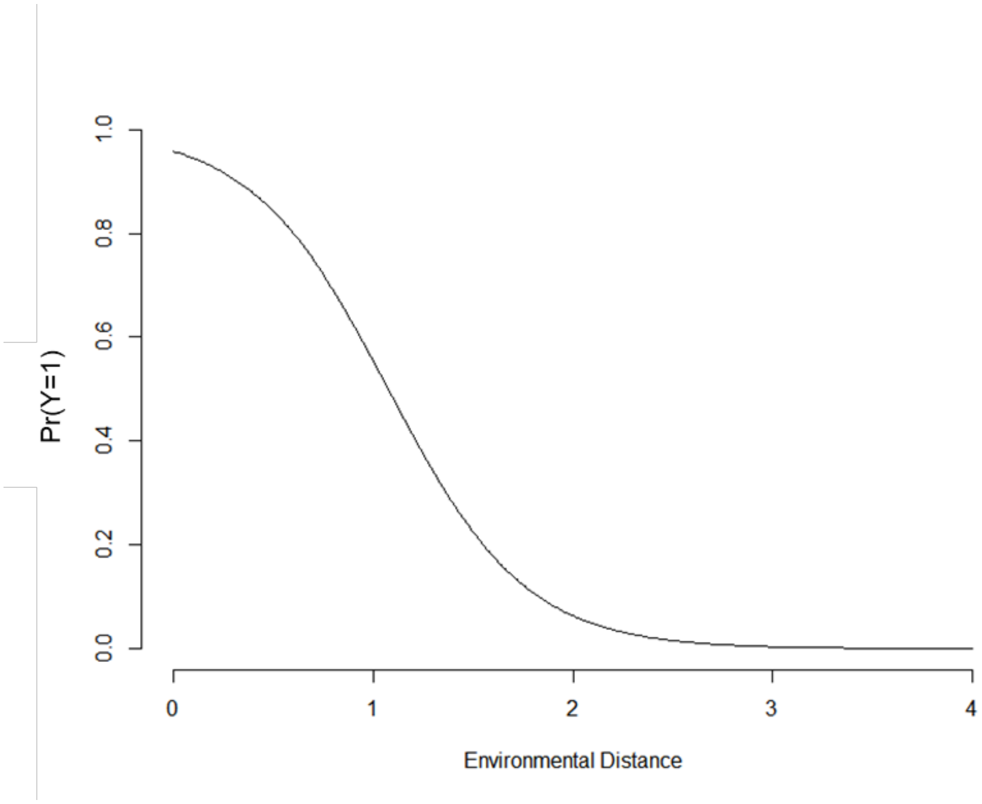
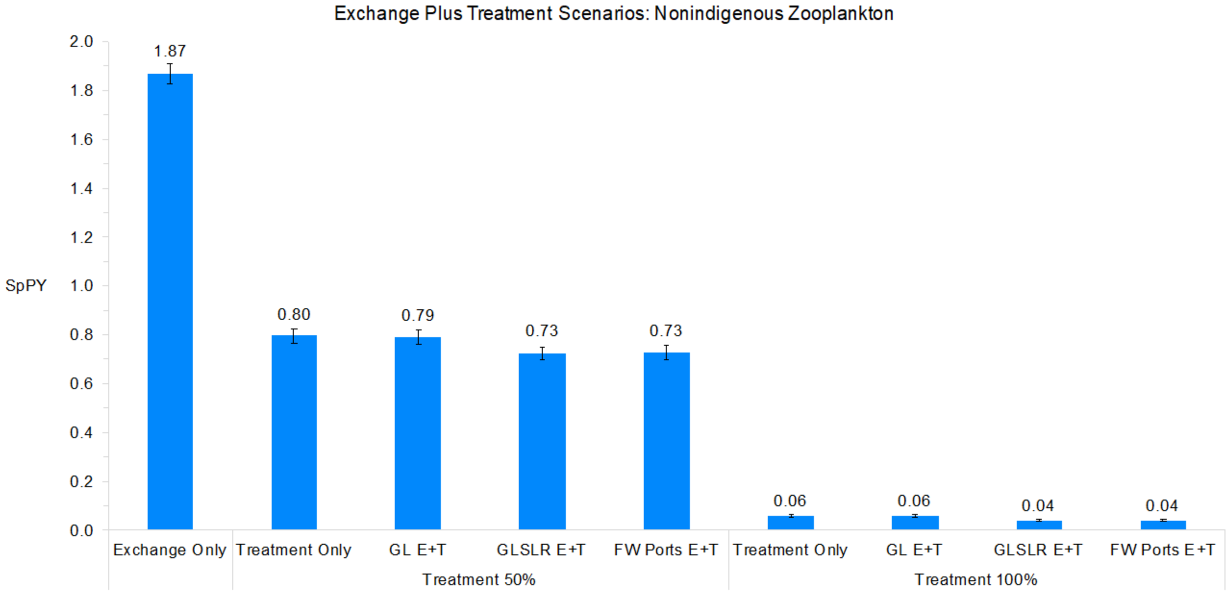


Figure A1. Environmental distance curve. Pr(Y = 1) represents the probability of species survival and establishment in the recipient port given the temperature match between the ballast source and destination ecosystems.



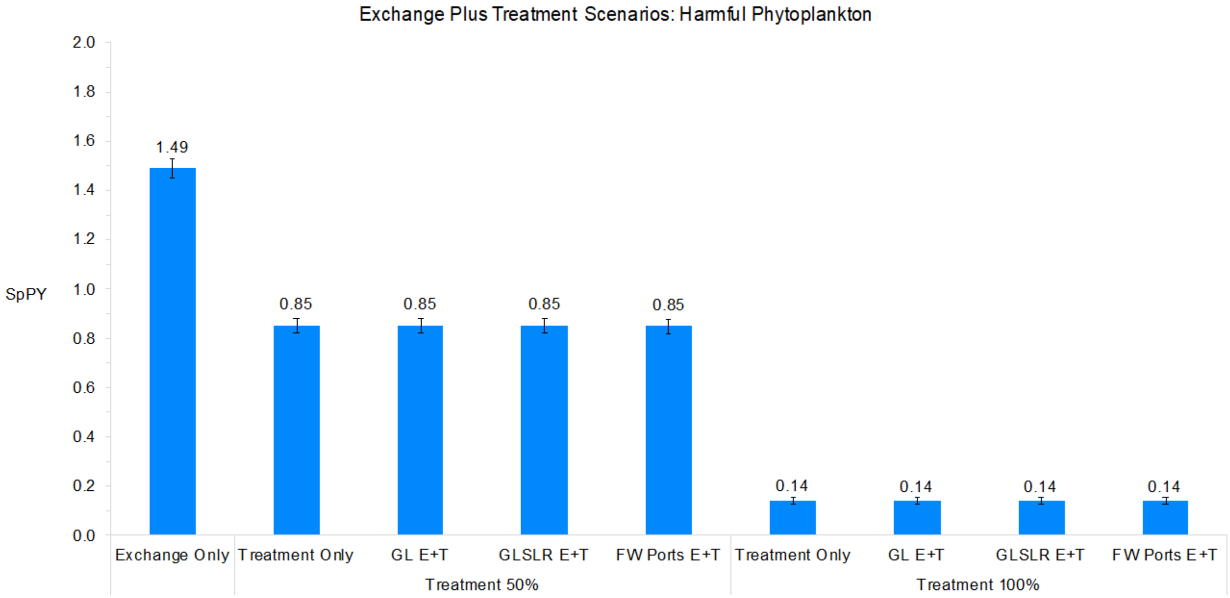


Figure A2. The expected number of species per year (SpPY) for nonindigenous zooplankton and harmful phytoplankton across Canada for the exchange plus treatment scenarios. The Great Lakes, Great Lakes-St. Lawrence River and all fresh water ports exchange plus treatment scenarios are denoted by GL, GLSLR, and FW (E+T), respectively. For treatment, either i) half of the treatment events successfully met D-2 (treatment 50%) or ii) all treatment events successfully met D-2 (treatment 100%). Ships were assumed to use treatment alone where ballast water management is not specified. The error bars represent the bootstrapped 95% confidence intervals of the mean of EPY across 1000 iterations.

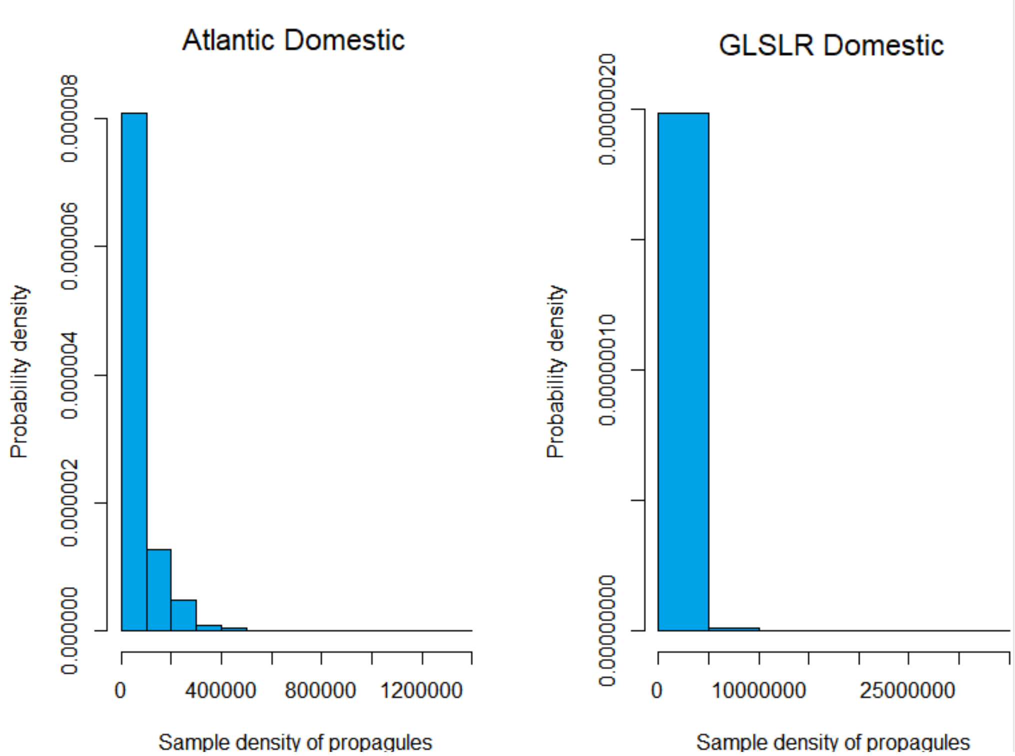


Figure A3. Probability distribution describing zooplankton sample densities among domestic transits in Atlantic Canada and the GLSLR. The zooplankton sample density distribution for domestic transits with Arctic source ports was assumed to be equivalent to that within Atlantic Canada.

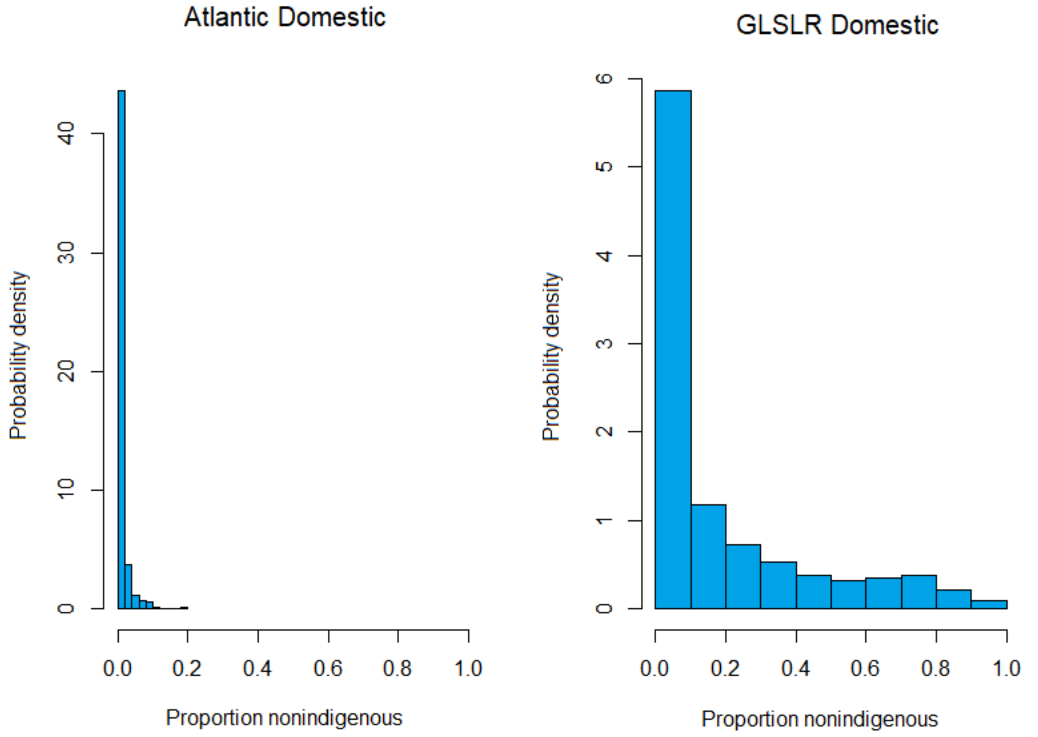


Figure A4. Probability distribution describing the proportion of nonindigenous zooplankton out of the total zooplankton population among domestic transits in Atlantic Canada and the GLSLR. The distribution of the proportion of nonindigenous zooplankton for transits with Arctic source ports was assumed to be equivalent to that within Atlantic Canada.

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