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SCIENCE ADVICE ON THE EFFECTIVENESS OF BALLAST WATER EXCHANGE PLUS TREATMENT AS A MECHANISM TO REDUCE THE INTRODUCTION AND ESTABLISHMENT OF AQUATIC INVASIVE SPECIES IN CANADIAN PORTS

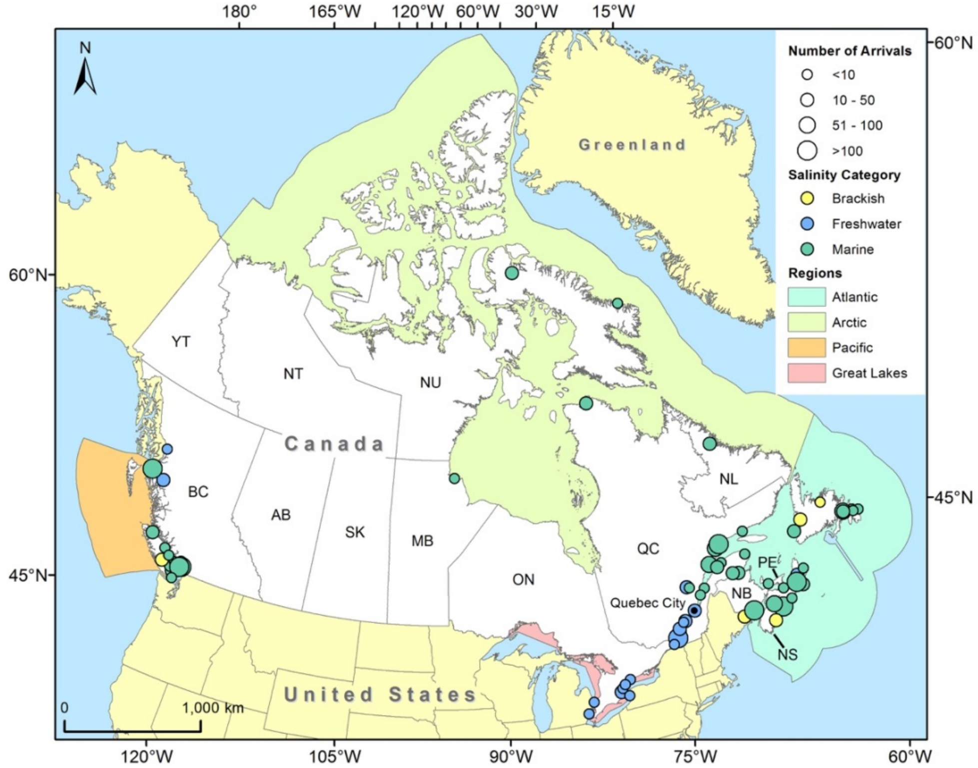

Figure 1. The Canadian geographic regions with the shipping ports examined in this study. The four Canadian regions of interest are the Pacific, Atlantic, Great Lakes-St. Lawrence River (GLSLR), and Arctic. The destination ports (n = 72) included in this study are displayed by the markers where their color and size represent their salinity category and number of ship-trip arrivals, respectively.

Context:

Aquatic invasive species are a significant environmental stressor with widespread ecological impacts including biodiversity loss. The movement of ballast water via commercial shipping is a high-risk pathway through which harmful and/or non-indigenous aquatic species are introduced into novel ecosystems. The current management strategy, ballast water exchange, has varied effectiveness across different habitat types, and will be gradually replaced with a ballast water performance standard with the aim to achieve more consistent reduction of invasion risk. The Government of Canada proposed that the combined use of these management strategies may potentially achieve even greater risk reductions in fresh and brackish water environments than either strategy could alone, but additional scientific research is required to inform policy makers and risk managers about whether the exchange plus treatment strategy should be applied in Canada.

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A risk assessment was developed to determine the effectiveness of exchange plus treatment at preventing the invasion of aquatic species in Canada compared to exchange or treatment alone. Models were created to estimate the expected number of non-indigenous zooplankton and harmful phytoplankton species establishments in the Canadian regions of interest based on initial population size, shared environmental characteristics between source and recipient ports, and the resulting likelihood that released organisms would establish viable populations in recipient ecosystems.

This Science Advisory Report is from the February 27-28, 2018 Science advice on ballast water exchange plus treatment. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Ballast water is a high-risk vector for the introduction of aquatic invasive species (AIS). AIS cause profound ecological changes, including biodiversity loss, changes in trophic dynamics, loss of fishery productivity, and introduction of disease. As a result of these ecological changes, invasions modify ecosystem services and generate direct and indirect economic damages.
- The following Science Advisory Report (SAR) is based on a model-based analysis of shipping and biological data to understand the implications of different management strategies (no management, ballast water exchange (BWE), ballast water treatment, and exchange plus treatment) across different regions in Canada.
- Two metrics were developed to assess establishment risk: the per trip probability that at least one species invasion occurs, and the number of species invasions per year. The number of species per year reflects the outcome of the per trip probability of invasion when shipping traffic is considered. To simplify the interpretation of results, these invasion metrics were converted to the number of trips until at least one species invasion occurs and the number of species invasions per decade.
- In general, when all vessels in this study adhere to the D-2 standard, the use of ballast water management systems (BWMS) is expected to provide a substantial reduction in establishment risk compared to BWE, for both assessment metrics.
- For the Great Lakes-St. Lawrence River (GLSLR) region, maintaining exchange in addition to treatment when the ballast source is brackish or fresh water would result in a lower number of harmful phytoplankton invasions than transitioning to a strategy that only uses BWMS.
- Exchange plus treatment would further reduce the risk of establishment compared to treatment alone for the GLSLR region when ballast water is treated using BWMS on all or half of the ship-trips. When all vessels meet the D-2 standard, the expected number of species per decade (SpPD) decreases from 1.61 (BWMS alone) to 1.28 (exchange plus treatment) for zooplankton and 0.61 (BWMS alone) to 0.45 (BWE plus BWMS) for phytoplankton. When BWMS are used on 50% of voyages, SpPD decreases from 5.15 (BWMS alone) to 4.52 (BWE plus BWMS) for zooplankton and 1.41 (BWMS alone) to 1.07 (BWE plus BWMS) for phytoplankton.
- For all other pathways in Canada, exchange plus treatment has variable effects compared to treatment alone. The most consistent risk reduction of adding exchange to treatment was observed for voyages destined to freshwater ports from freshwater or brackish source ports. Exchange plus treatment is less effective than treatment alone for voyages originating from

marine ports and terminating in freshwater ports when 100% of transits meet the D-2 standard.

- In the event that only 50% of transits meet the D-2 standard, exchange plus treatment provides an important reduction in establishment risk compared to treatment alone when the ballast source is fresh water.

INTRODUCTION

Aquatic invasive species (AIS) cause great ecological stress on native species through competition, predation, habitat alteration, and spread of disease (Mack et al. 2000). Consequently, AIS cause local and broad-scale biodiversity loss including contributing to the decline in populations of numerous fishery species and species at risk in Canada (Mills et al. 1993, Mack et al. 2000, Dextrase and Mandrak 2006). Ballast water, which is used by large commercial vessels to control their stability and movement, is a prominent vector for the dispersal of AIS (NRC 1996). When cargo is unloaded, vessels inadvertently pump aquatic species along with ambient port water into ballast tanks. The organisms that survive the voyage are then released into recipient ports when cargo is loaded onto the vessel and the ballast water is discharged. A subset of the discharged viable species may survive in the novel ecosystem, and a small portion of those species may establish self-sustaining populations.

Considerable scientific research has been conducted to understand the role of ballast water as a vector for AIS dispersal (Ruiz et al. 2007, Bailey et al. 2011, Reid 2012, Simard et al. 2011, Casas-Monroy et al. 2014, Bailey 2015), which is essential for the development of science-based management strategies aimed at curbing invasions attributed to ballast water discharge. The current management strategy of ballast water exchange (BWE) has greatly reduced invasion rates in the Great Lakes (Bailey et al. 2011, Bailey et al. 2012), but its effectiveness is varied in coastal regions with high salinity ports (Casas-Monroy et al. 2014). To achieve uniform invasion risk reduction across different habitat types, ballast water performance standards that effectively require the use of onboard ballast water management systems (BWMS) will be gradually implemented (IMO 2004). To provide the greatest feasible protection to Canadian aquatic ecosystems, the Canadian Government proposed the combined use of BWE and BWMS in at least fresh and brackish water ecosystems (IMO 2010). Although preliminary studies have determined the risk reduction potential of exchange plus treatment for freshwater ecosystems (Briski et al. 2013, Briski et al. 2015), additional research is required to determine the effectiveness of this multidimensional strategy applied regionally and across different habitat types.

Ballast water exchange

BWE involves discharging ballast water in the ocean and refilling ballast tanks with mid-ocean water with the purpose of decreasing the concentration of high-risk source port organisms in ballast tanks (Bailey 2015). The logic behind BWE is most harmful freshwater and coastal organisms in ballast tanks are ejected from tanks when ballast water is discharged at sea (Ruiz et al. 2007), while any retained freshwater and coastal residual organisms are exposed to large and sudden changes in salinity, usually to lethal levels, when tanks are refilled with oceanic water (Reid 2012). The mid-oceanic species taken aboard during the exchange are expected to have reduced survival when discharged in freshwater and coastal ports (Reid 2012). Therefore, one of the primary mechanisms of action of BWE is environmental mismatching, where the probability of survival of propagules is reduced by exposing them to inhospitable environmental conditions and, consequently, the effectiveness of BWE is dependent on the environmental tolerances of species and the environmental correspondence between the ballast source and recipient locations (Bailey et al. 2006, Gray and MacIsaac 2010, Casas-Monroy et al. 2014).

The environmental mismatch imposed by BWE does not equally affect all AIS, since certain species have adaptations that allow them to tolerate a broad range of environmental conditions. For example, euryhaline species can tolerate a wide range of salinities, surviving in both fresh and marine waters, and cysts or diapausing eggs produced by certain freshwater species can tolerate exposure to mid-ocean water, successfully hatching once returned to benign environments (Bailey et al. 2006, Gray and MacIsaac 2010, Reid 2012).

The success of BWE is dependent on the degree of environmental mismatch between the ballast source and destination locations. BWE is most effective at mitigating the delivery of high-risk propagules when used between freshwater ports, where the environmental mismatch is the greatest; however, certain species may be able to survive exposure to mid-ocean water and invade recipient freshwater ecosystems (Santagata et al. 2008, Ellis and MacIsaac 2009, Bailey et al. 2011, Reid 2012, Casas-Monroy et al. 2014). On the other hand, BWE is less effective at protecting coastal ecosystems due to the reduced effects of environmental mismatching; high-risk residual coastal species may survive exposure to mid-ocean water, and marine species taken aboard during the exchange may survive in recipient coastal ecosystems (McCollin et al. 2008, Cordell et al. 2009, Simard et al. 2011, Reid 2012, Roy et al. 2012, Adams et al. 2014, Casas-Monroy et al. 2014, Linley et al. 2014, Casas-Monroy et al. 2016).

The variability in efficacy of BWE at protecting coastal ports was a primary reason for considering BWE as a short-term solution until more universal strategies such as BWMS could be implemented.

Ballast water management systems

The International Maritime Organization’s (IMO) International Convention for the Control and Management of Ships’ Ballast Water and Sediments – adopted in 2004 – aims to reduce invasion risk by targeting the propagule pressure component of the invasion process through the application of Regulation D-2, a propagule discharge standard (Table 1; IMO 2004). Vessel types that must comply with the D-2 standard as defined in this Convention are expected to use an approved shipboard BWMS, which typically involve filtration (e.g., screen or disc filters, hydrocyclones) followed by at least one wastewater disinfection process (e.g., ultra violet radiation, electrolysis, chemical injection; Mouawad Consulting 2013). Depending on the type of treatment process, water may be managed both during uptake before entering ballast tanks and discharge (e.g., ultra violet radiation), or only during ballast water uptake (e.g., electrolysis; Mouawad Consulting 2013).

At least 69 BWMS are approved for use by regulating Administrations, which have demonstrated ability to manage ballast water at or below the organism discharge limits set by the D-2 standard during Type Approval testing (see IMO website). When functioning properly, numerous studies have determined that an array of treatment processes are effective at decreasing the concentration of plankton (de Lafontaine et al. 2009, Gregg et al. 2009, Casas-Monroy et al. 2018). Nevertheless, treatment systems susceptible to malfunctions may not reliably treat ballast water to the D-2 standard (e.g., turbid water may cause equipment to fail; Cangelosi et al. 2011, Briski et al. 2013, Paolucci et al. 2015), but the rate of malfunctions may decrease with improvements to treatment technologies in the future.

Table 1. The D-2 ballast water discharge standard from the International Convention for the Control and Management of Ships' Ballast Water and Sediments (IMO 2004; Table 1 in Casas-Monroy et al. 2014).

Category	Size Range	Discharge Standard
Phytoplankton	≥ 10μm - < 50μm	< 10 cells/ml
Zooplankton	≥ 50μm	< 10 organisms/m^3
Microbes	*Vibrio cholera*	1 CFU per 100ml or 1 CFU per 1g (wet weight) zooplankton samples
	Escherichia coli	250 CFU per 100ml
	Intestinal Enterococci	100 CFU per 100ml

Exchange plus treatment

The Canadian Government has the authority to implement stricter ballast water regulations than those outlined in the IMO's Convention in order to provide adequate protection to Canada's aquatic ecosystems (Transport Canada 2012). As a result, in 2010, Canada proposed that using BWE in concert with BWMS may achieve greater reduction in invasion risk than BWMS alone for fresh and brackish water ecosystems, as this multidimensional strategy combines the effects of a salinity barrier through BWE and propagule pressure reduction by BWMS (IMO 2010). Additionally, in the event that BWMS malfunction, BWE can be used as a backup strategy to manage ballast water.

Since 2010, land-based and shipboard studies have concluded that in relation to treatment alone, exchange plus treatment may result in greater reductions in the arrival of high-risk freshwater and euryhaline propagules, providing increased protection to freshwater environments (Briski et al. 2013, Briski et al. 2015). However, more research is needed to determine the effectiveness of exchange plus treatment if implemented in different aquatic habitats or regions with contrasting habitat types.

Objective

The objective of this study was to conduct a risk assessment to estimate the expected AIS establishment rate in Canada attributed to ballast water discharge, under different management scenarios. The focus was on the effectiveness of exchange plus treatment compared to that of either exchange or treatment individually, as it was important to determine if this alternative management strategy produces greater reductions in invasion risk. This study also considered the possibility that BWMS may malfunction on a proportion of voyages and determined the effect of using BWE as a backup strategy on AIS establishment rates.

ASSESSMENT

The analysis of Canadian ecosystems incorporated six ballast water management scenarios (Table 2). To consider the possibility that BWMS may malfunction, scenarios were created where the D-2 standard was applied to half the voyages. This proportion of voyages (50%) was chosen as an example, given unpublished data (samples of treated ballast water) gathered prior to the IMO Convention entering into force in 2017; it is acknowledged that the proportion of voyages meeting the D-2 standard is likely to improve with advancements in BWMS technologies and operational experience gained.

Table 2. Scenarios of management strategies examined in this study.

Management Scenario	Definition
No-Management	The control scenario where neither exchange nor treatment occurred.
Exchange-Only	BWE occurred on all ship-trips. It was assumed that the total concentration of organisms and the proportion that were harmful or non-indigenous did not change pre- vs. post-exchange, and that BWE was 100% efficient at purging source port organisms. Therefore, only species belonging to mid-ocean communities were modelled following BWE.
Treatment-Only (100%)	The no-management scenario was modelled with the application of the IMO D-2 standard on 1) 100%, and 2) 50% of voyages. For the second scenario, it was assumed that untreated ballast water was discharged on half of the ship-trips.
Treatment-Only (50%)	
Exchange Plus Treatment (100%)	The exchange-only scenario was modelled with the application of the IMO D-2 standard on 1) 100%, and 2) 50% of trips. For the second scenario, it was assumed that ballast water was only managed using BWE on half of the voyages.
Exchange Plus Treatment (50%)	

The management scenarios were applied to five shipping pathways composed of combinations of four Canadian geographic regions and two traffic pathways (i.e., international or domestic shipping activity; Figure 1 and Table 3). Furthermore, an All Shipping Pathways option was created, which combined all five shipping pathways, to determine the overall effect of the management strategies when applied to Canada as a whole.

Table 3. The shipping pathways examined in this study. See Figure 1 for a map of the geographic boundaries of the Canadian regions.

Shipping Pathway	Definition
Pacific International	Ships destined for ports in British Columbia from foreign source ports.
Atlantic International	Ships destined for ports in Atlantic Canada from foreign source ports. The Atlantic region included the St. Lawrence River downstream of and excluding Québec City, and did not include mainland Labrador.
Great Lakes-St. Lawrence River (GLSLR) International	Ships destined for Canadian ports in the Great Lakes or the St. Lawrence River from foreign source ports. The GLSLR region included Canadian ports upstream of and including Québec City. Transits between American and Canadian ports within this region were not included.
Arctic International	Ships destined to ports in the Canadian Arctic from either foreign source ports (excluding U.S. ports in the GLSLR) or other Canadian regions (domestic ship trips). The Arctic region included areas delineated by PAME’s 2013 Arctic LME map, including mainland Labrador (PAME 2013).
Arctic Domestic	
All Shipping Pathways	All of the above shipping pathways of interest are combined.

As the performance of BWE is mainly dependent on the magnitude of the salinity barrier created through environmental mismatching, it is essential to assess the effectiveness of each strategy across different habitat types. Therefore, the management scenarios were applied considering the multiple source and recipient port salinity combinations within each shipping pathway. The salinity categories used in this study are ≤ 5.0‰ for fresh, 5.1-18.0‰ for brackish, and ≥ 18.1‰ for marine waters (Remane and Schlieper 1972).

Non-indigenous species (NIS) of zooplankton and harmful phytoplankton species were the two taxonomic groups used to determine the species establishment rate under each management scenario. Hereafter, the collective reference of harmful species or harmful propagules is used for harmful phytoplankton species and zooplankton NIS.

Data sources

This study utilized much of the biological and shipping data used by Casas-Monroy et al. (2014), which incorporated biological data from the Canadian Aquatic Invasive Species Network (Humphrey 2008, Klein et al. 2009, Bailey et al. 2011, Briski et al. 2012a,b, Casas-Monroy 2012, DiBacco et al. 2012, Roy et al. 2012, Adebayo et al. 2014). The shipping data obtained from Casas-Monroy et al. (2014) were sourced from the Canadian Coast Guard’s Information System on Marine Navigation, the U.S. National Ballast Information Clearinghouse, and Transport Canada Ballast Water Database, and were used for Pacific International, Atlantic International, and Great Lakes-St. Lawrence River (GLSLR) International pathways. The data sources used in this study also included zooplankton data from Chan et al. (2015) for the Arctic International pathway and more recent Arctic shipping data from Fednav International Ltd., the Canadian Coast Guard Northern Canada Vessel Traffic Services, and the Transport Canada Ballast Water Database. The water temperature and salinity data used to determine the match between the ballast source and recipient port was acquired from Keller et al. (2011) and World Ocean Atlas 2013 Vol. 2 (Locarnini et al. 2013, Zweng et al. 2013), with a few updates applied to correct the salinities of inland freshwater ports.

Summary of the risk assessment model

To determine species establishment rate under each management scenario, this model assessed critical components of the invasion process, including the initial population size of organisms released from ballast water, the probability of species survival in recipient ecosystems, and the likelihood of establishment.

First, a one-year iteration of shipping activity describing the geographic source to recipient port transits of vessels was conducted. This was necessary to determine the frequency and spatial distribution of transported species to Canadian ports within each shipping pathway, and to identify the unique source and recipient port combinations for the survival component of the model.

The number of harmful species (or non-indigenous, if zooplankton) and their initial population sizes were determined for each trip based on empirical ballast water sample data (i.e., biological samples obtained from ships), which were pathway-specific and categorized by taxonomic group–phytoplankton or zooplankton. The sample concentration of all propagules was estimated for a given trip, which included both harmful and non-harmful species. Since the concentration of all propagules contained in a ballast tank could be greater or less than the sample concentration, the most likely total propagule concentration in the entire ballast tank was estimated based on the selected sample concentration. It was during this step that the D-2 standard was applied by reducing the total tank propagule concentration to the organism discharge limits (see Table 1 for the assigned discharge limits and associated size ranges for phytoplankton and zooplankton). Then, the proportion of harmful propagules out of the total tank concentration was estimated, which considered the harmful status of species specific to each geographical region (e.g., one zooplankton species may be indigenous to the GLSLR but non-indigenous to the Pacific Coast). Furthermore, the number of harmful species and their relative concentrations out of the proportion of harmful propagules was estimated for a given voyage. Therefore, each voyage had a unique distribution of propagules with a defined number of harmful species, capturing the variation between trips.

Once the number and relative concentrations of harmful species on a voyage was determined, the probability that each transported species will survive upon release into the recipient ecosystem was estimated based on the environmental match between the source and recipient locations. Water temperature and salinity were the environmental conditions chosen to estimate the probability of survival, as they are robust variables that govern where aquatic species can live. It was during this step that the effect of BWE was modelled through the representation of a post-exchange mid-ocean community, with species survival probabilities reflecting the environmental conditions of the location of exchange relative to recipient port conditions. The species that survived in the recipient ecosystem continued onto the establishment component of the model.

The final component in the model was to determine whether each surviving species for a given discharge event (i.e., one trip) will establish a viable population in the recipient ecosystem. This was accomplished by using a species establishment probability equation that incorporated the previously determined initial population size and the per-propagule probability of establishment of the species. To determine the probability that a single propagule of a species becomes established (a mathematical, not a biological parameter), the upper maximum limit was set by parthenogenetic species, with the remaining species – which were assumed to be the vast majority of species in ballast tanks – having substantially lower per propagule probabilities of establishment. Then, based on a species' probability of establishment, a statistical method was applied to produce a binary outcome of either establishment or extinction. The success or failure of establishment was conducted for each surviving species per discharge event across all annual voyages within each shipping pathway.

For each shipping pathway, the one-year simulation of shipping activity (i.e., voyages and subsequent discharge events) was repeated 1000 times, and the long-run average was produced (i.e., the expected outcome). The two metrics of establishment risk used to compare the relative performance of the management scenarios were the per trip probability that at least one species invasion occurs and the number of species invasions per year. The number of species invasions per year reflects the annual number of species invasions when shipping traffic is considered; whereas, the per trip probability that at least one species invasion occurs is largely independent of shipping volume, and captures the risk status of individual trips within a region. To simplify the interpretation of the results, these invasion metrics were converted to the number of trips until at least one species invasion occurs, and the number of species invasions per decade.

RESULTS

Since there is considerable uncertainty associated with modelling invasion rates, greatest emphasis should be placed on relative differences between management scenarios. Ecologically significant differences in invasion rates across management scenarios are not described in this study, since risk managers and policy makers decide on the level of acceptable risk. Note that the results of this study reflect the actual expected invasion rates under the application of the D-2 standard for zooplankton NIS or harmful phytoplankton only; it is possible that additional establishments may occur (e.g., native zooplankton; non-harmful but NIS phytoplankton).

Based on the results presented in Figure 2, when all shipping pathways were combined, BWE alone resulted in the highest invasion rates with 22.13 and 18.08 expected number of species invasions per decade (SpPD) for zooplankton and phytoplankton, respectively, second to no-management, while treatment-only (100%) reduced SpPD to 3.69 (zooplankton) and 5.6 (phytoplankton). The effectiveness of exchange plus treatment compared to treatment alone was variable among the shipping pathways, with exchange plus treatment producing a lower expected invasion rate than treatment alone in GLSLR International for both zooplankton (exchange plus treatment: 1.28 SpPD; treatment alone: 1.61 SpPD) and phytoplankton (exchange plus treatment: 0.45 SpPD; treatment alone: 0.61 SpPD), and in Arctic International for zooplankton (exchange plus treatment: 0.06 SpPD; treatment alone: 0.09 SpPD). For all other shipping pathways (including in Arctic International for harmful phytoplankton), exchange plus treatment and treatment alone had similar species establishment rates for zooplankton (exchange plus treatment ranging from 0.9 – 1.5 SpPD; treatment alone ranging from 0.14 – 1.49 SpPD) and phytoplankton (exchange plus treatment ranging from 0.2 – 4.09 SpPD; treatment alone ranging from 0.26 – 4.37 SpPD). See Table A.1 (Appendix 1) for SpPD values as percentage change.

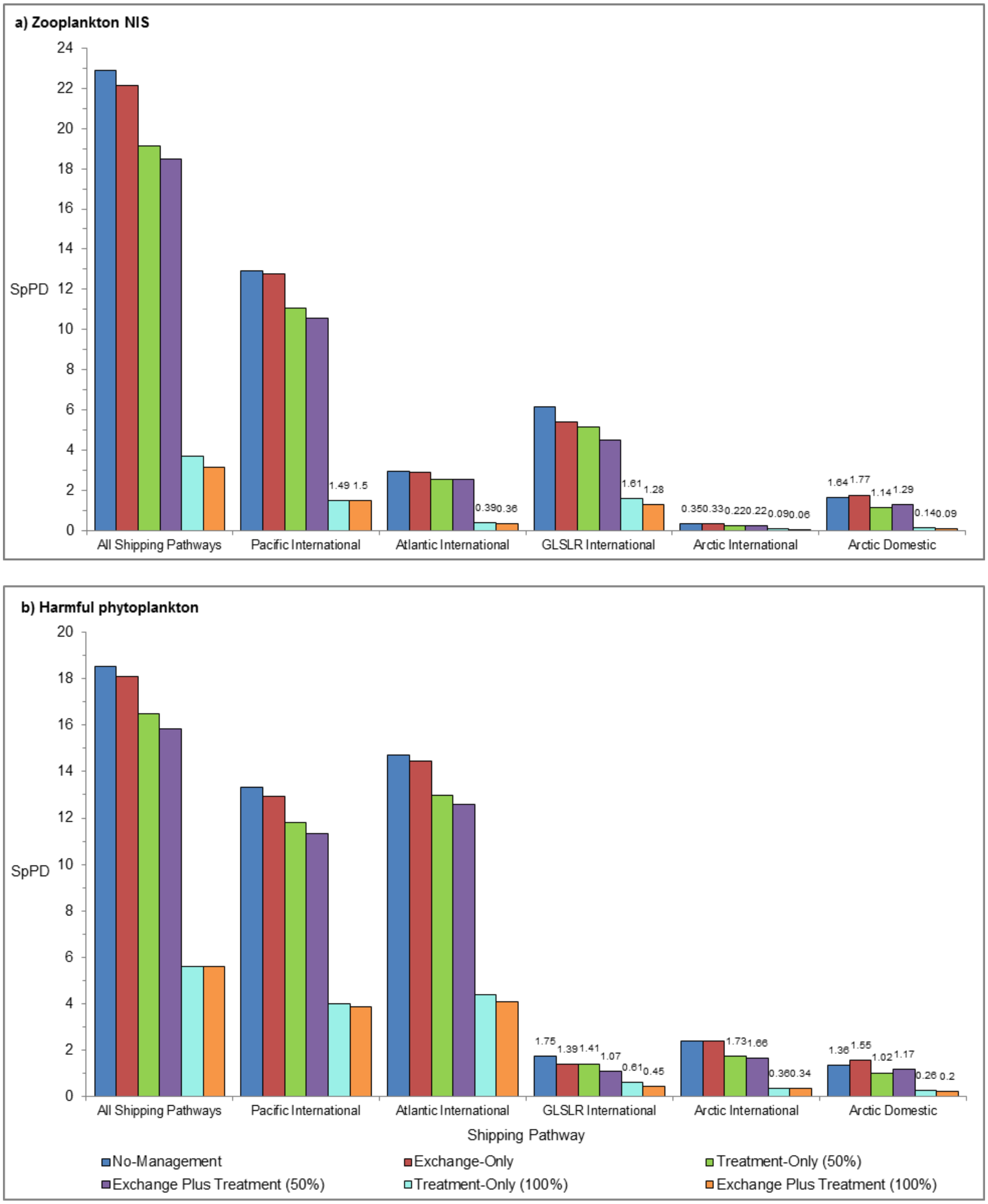

Figure 2. Expected number of species invasions per decade (SpPD) for each management scenario within each shipping pathway for a) zooplankton NIS and b) harmful phytoplankton results. The management scenarios where the IMO D-2 standard has been applied to all and half of the ship-trips are denoted by 100% and 50%, respectively.

In the GLSLR International pathway, treatment-only (50%) resulted in a similar rate of decadal species invasions to that of exchange-only for both zooplankton and phytoplankton, which was further reduced when these strategies are used in concert (zooplankton: treatment-only 50% = 5.15 SpPD, exchange-only = 5.38 SpPD, combined = 4.52 SpPD; phytoplankton: treatment-only 50% = 1.41 SpPD, exchange-only = 1.39 SpPD, combined = 1.07 SpPD). For the other shipping pathways, the addition of BWE to treatment (50%) shifted the observed range of SpPD from 0.22 – 11.07 (treatment-only, 50%) to 0.22 – 10.57 (exchange plus treatment, 50%) for zooplankton, and from 1.02 – 12.98 (treatment-only, 50%) to 1.17 – 12.6 (exchange plus treatment, 50%) for phytoplankton.

As seen in Figure 3, when all shipping pathways were combined, managing ballast water by using only exchange resulted in the expected number of trips until at least one species invasion occurs (NTOI) ranging from 116 – 3991 (zooplankton) and 64 – 1655 (phytoplankton), depending on source and recipient environmental conditions, while substantial increases in the NTOI were achieved under the treatment-only (100%) scenario (between 435 – 227500 NTOI for zooplankton and 429 – 10111 NTOI for phytoplankton). Of the recipient port salinity categories, freshwater received the greatest benefits from exchange plus treatment compared to treatment alone when the ballast source was brackish (zooplankton: exchange plus treatment, 1622 NTOI vs. treatment alone, 507 NTOI; phytoplankton: exchange plus treatment, 1973 NTOI vs. treatment alone, 730 NTOI) or fresh water (zooplankton: exchange plus treatment, 1224 NTOI vs. treatment alone, 435 NTOI; phytoplankton: exchange plus treatment, 1938 NTOI vs. treatment alone, 633 NTOI). For the marine source to freshwater recipient port pair, exchange plus treatment had a slightly lower NTOI of 1427 (zooplankton) and 1624 (phytoplankton) relative to the NTOI of treatment-only (1843 for zooplankton and 2030 for phytoplankton).

In the event that the D-2 standard was only applied on half of the transits, exchange plus treatment had varied effectiveness compared to treatment alone among the source and recipient port salinity pairs. Exchange plus treatment had the most consistent benefits in establishment risk reduction when source ports were freshwater for both zooplankton (exchange plus treatment 50%, range of 298 – 10581 NTOI vs. treatment-only 50%, 100 – 6149 NTOI) and phytoplankton (exchange plus treatment 50%, 154 – 3346 NTOI vs. treatment 50%, 89 – 1928 NTOI). Similar to the trend observed when the D-2 standard was applied on 100% of ship-trips, the greatest benefit from exchange plus treatment over treatment alone occurred for the freshwater to freshwater port pair (zooplankton: 298 vs. 100 NTOI; phytoplankton: 616 vs.166 NTOI). See Table A.2 (Appendix 1) for NTOI values as percentage change.

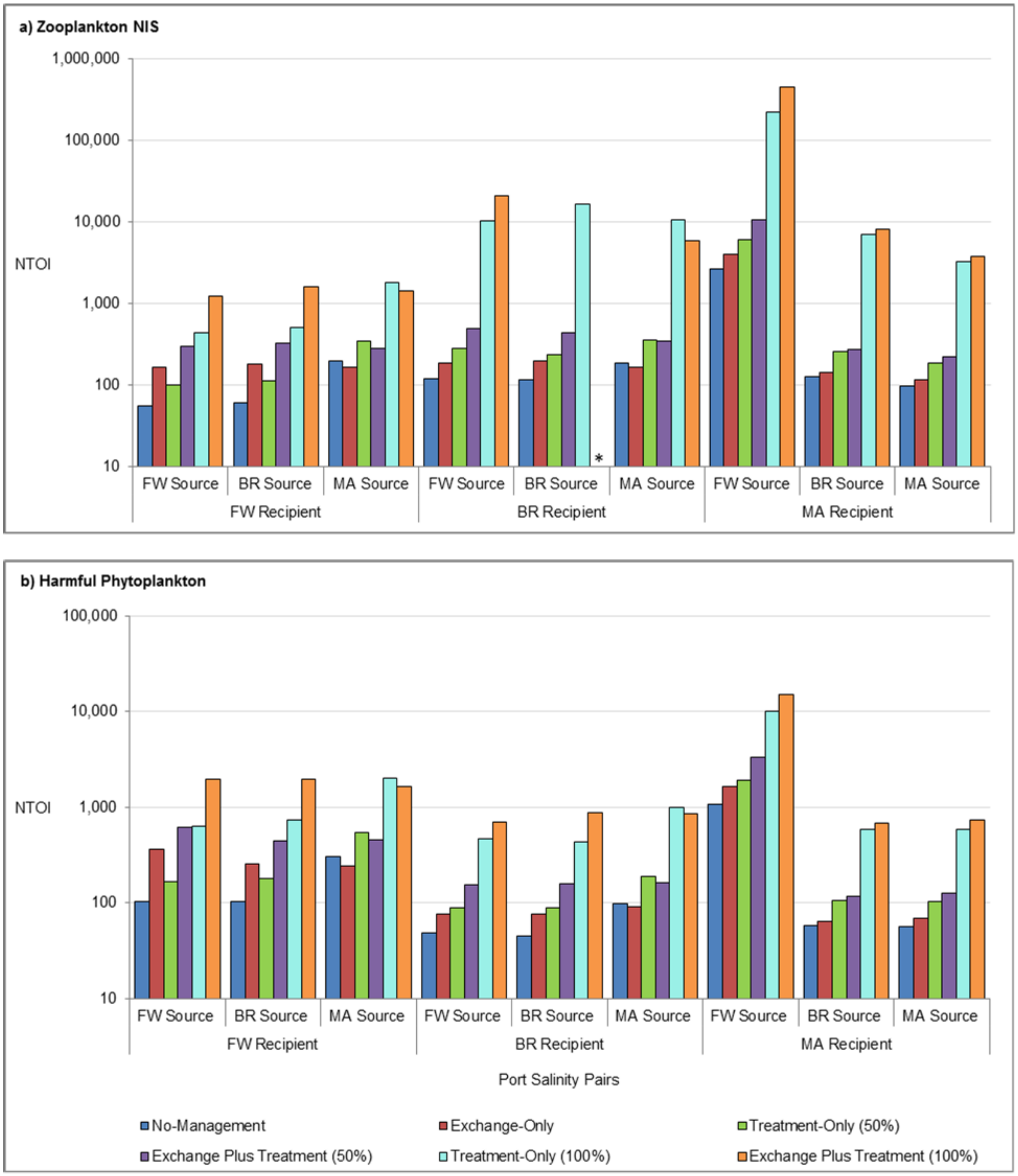

*Figure 3. Expected number of trips until at least one species invasion occurs (NTOI) under various management scenarios for each port salinity pair when all shipping pathways are combined for a) zooplankton NIS and b) harmful phytoplankton. The salinity categories of fresh, brackish, and marine water are each denoted by FW, BR, and MA. The management scenarios where all and half of the ship-trips are applied with the D-2 standard are denoted by 100% and 50%, respectively, and * denotes the scenarios that would have an infinite number of trips until one species invasion occurs. The y-axis is on a logarithmic scale.*

Sources of Uncertainty

- The number of ship arrivals and ballast water discharge quantities can vary significantly from year to year, and future increases in Arctic shipping activities may increase both the number of discharges and the variety of source ports (diversity of propagules).
- There is uncertainty surrounding the number of zooplankton NIS and harmful phytoplankton in ballast for pathways, especially where biological sample sizes were small or unavailable (e.g., Arctic pathways).
- Environmental conditions (temperature and salinity) vary temporally and spatially, and are not usually available at the resolution of ports (near-shore, shallow coastal waters).
- Risk-release relationships, used to inform establishment, were estimated based on a limited number of studies. The true parameters underlying these relationships are unknown. Meaningful differences relative to those used in the study would lead to different invasion rates, but relative results among management scenarios would remain constant.
- Survival was estimated as a function of environmental matching (temperature, salinity), and did not include other measures of habitat suitability (e.g., abiotic factors like nutrient availability and biotic factors like competition or predation).

CONCLUSIONS AND ADVICE

1) What is the recommended protocol for ships to undertake exchange plus treatment of ballast water and what is its mechanism of action?

There are two protocols for ships to undertake exchange plus treatment: treatment plus exchange plus treatment (T+E+T) and exchange plus treatment (E+T). During T+E+T, ballast water is managed using the BWMS with every loading event (at port and mid-ocean) whereas, for E+T, the BWMS is used only during the intake of mid-ocean water during BWE. The primary mechanism of action of both protocols is to reduce the probability of survival of AIS through environmental mismatching, and to decrease the propagule pressure of arriving species through treatment. E+T places less stress on BWMS since oceanic water is typically less challenging to treat than harbour water and requires lower effort and cost due to fewer treatment steps and less usage of the BWMS (C. Wiley, IMO Marine Environment Protection Committee, pers. comm., Briski et al. 2013). The disadvantage of E+T is that ballast water initially loaded at ports is not managed, such that untreated ballast residuals inside tanks may mix with the incoming treated water after exchange, although BWMS that operate during ballast water discharge may reduce this risk. Under ideal (less challenging) port water conditions, T+E+T provides superior protection against invasions compared to E+T since there is never any unmanaged ballast water entering ships' tanks. Additionally, the T+E+T protocol meets current IMO regulations which prohibit the discharge of untreated ballast water at any location. The drawback of T+E+T is that challenging port water conditions may cause BWMS to malfunction and require significant maintenance or repair. Given the large differences in our model results when the D-2 standard is applied on 100% vs. 50% of voyages, it is important to strive for the greatest functionality of the BWMS. As a result, the recommended protocol is to conduct E+T.

2) When compared with the use of a Ballast Water Management System (BWMS), to what extent would exchange plus treatment reduce the risk that non-indigenous species will arrive and survive in Canada, and what would be the expected reduction in the rate of new establishments?

For the GLSLR pathway, if all ballast water is treated to the D-2 standard, utilizing a treatment alone strategy would result in 0.61 harmful phytoplankton species expected to establish per decade, while the invasion rate would be reduced to 0.45 SpPD under an exchange plus treatment strategy. For all other pathways in Canada, exchange plus treatment has little effect on the rate of harmful phytoplankton establishment compared to treatment alone. Considering zooplankton NIS establishment, exchange plus treatment may result in a lower rate of establishment than treatment alone for the GLSLR International (exchange plus treatment, 1.28 SpPD vs. treatment only, 1.61 SpPD) and Arctic International pathways (exchange plus treatment, 0.06 SpPD vs. treatment only, 0.09 SpPD), while there was little difference in invasion rates between these two management scenarios for all other pathways.

3) Which Canadian ports would benefit most from a requirement for exchange plus treatment considering the key factors related to efficacy of exchange plus treatment (i.e., salinity and temperature)?

Freshwater ports in the GLSLR region – or all freshwater ports in Canada – would receive the most benefit from a requirement for exchange plus treatment compared to treatment alone regarding introductions of zooplankton NIS and harmful phytoplankton, when transits originate from fresh or brackish water ports and meet the D-2 standard; for GLSLR International, the difference in effectiveness between these two management strategies was greater for phytoplankton than zooplankton.

4) When compared to the use of treatment alone, how would exchange plus treatment affect the expected rate of new establishments in the case of ballast water that does not meet the standards in Regulation D-2, for example due to a BWMS failure?

For the GLSLR International pathway, exchange plus treatment may lower species establishment rates compared to treatment alone for zooplankton NIS (4.52 vs. 5.15 SpPD) and harmful phytoplankton (1.07 vs. 1.41 SpPD), when the D-2 standard is applied to 50% of transits.

When 50% of transits meet the D-2 standard, exchange plus treatment may be more effective at mitigating non-indigenous zooplankton and harmful phytoplankton invasion rates than only BWMS, when the ballast source is fresh water. The effectiveness of exchange plus treatment is greatest when both source and recipient ballast water ports are fresh water, where 298 and 616 trips until at least one species invasion occurs are expected under the exchange plus treatment strategy for zooplankton NIS and harmful algae, respectively.

5) What circumstances would justify revisiting this advice in the future?

The advice may be revisited if ballast water organism concentration or composition, environmental conditions, shipping patterns, proportion of voyages meeting the D-2 standard, or available data describing these conditions change in the future. Should data become available indicating organism concentration or composition for any pathway or management strategy deviate significantly from the inputs used in this analysis, or environmental conditions change such that temperature and/or salinity conditions in source or recipient ports deviate significantly from the inputs used in this analysis, the advice may be revisited to account for changes in introduction effort and changes in survival probability. Additionally, given that the overall effectiveness of management scenarios involving BWE is influenced by shipping activity between specific port-salinity pairs (e.g., freshwater to freshwater vs. marine to freshwater), it would be worthwhile to revisit the advice if there are any major changes in shipping traffic patterns (e.g., an increase in freshwater to freshwater ship-trips). Lastly, different values used to define risk-release relationships (as expected with increased scientific knowledge) would lead to different absolute invasion rates, but would not change the relative effectiveness of different management strategies.

Recommendations

- To further inform the risk reductions associated with exchange plus treatment in the event that ships are not able to comply with the D-2 standard, data should be collected on organism concentrations in treated ballast water for a representative sample of vessels.
- Address the lack of data on ballast water movements within Canada (e.g., volume, source) and provide more up-to-date data on ballast water transported to Canada, which would help support current and future research and science advice.

OTHER CONSIDERATIONS

BWE acts to change the community composition of plankton carried in ships' ballast tanks, reducing the abundance and diversity of coastal species and adding oceanic species. Species-specific changes in risk were not considered in this evaluation of the efficacy of BWE.

The risk-release relationship, which describes how propagule pressure relates to the establishment success of an introduced population, is poorly quantified and highly context-dependent, considering both biotic and abiotic factors.

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SOURCES OF INFORMATION

This Science Advisory Report is from the February 27-28, 2018 Science advice on ballast water exchange plus treatment. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX 1

Table A.1. Percentage change in SpPD in relation to multiple management scenarios within each shipping pathway for both zooplankton NIS and harmful phytoplankton. The management scenarios where all and half of the ship-trips are applied with the IMO D-2 standard are denoted by 100% and 50%, respectively.

Taxonomic Group	Shipping Pathway	No-Management to Exchange-Only	No-Management to Treatment-Only (50%)	No-Management to Exchange Plus Treatment (50%)	No-Management to Treatment-Only (100%)	No-Management to Exchange Plus Treatment (100%)	Exchange-Only to Treatment-Only (50%)	Exchange-Only to Exchange Plus Treatment (50%)	Exchange-Only to Treatment-Only (100%)	Exchange-Only to Exchange Plus Treatment (100%)
Zooplankton NIS	All Shipping Pathways	-3.36	-16.46	-19.21	-83.89	-86.16	-13.56	-16.40	-83.33	-85.68
	Pacific International	-1.39	-14.45	-18.32	-88.49	-88.41	-13.24	-17.16	-88.32	-88.24
	Atlantic International	-1.69	-12.88	-13.90	-86.78	-87.80	-11.38	-12.41	-86.55	-87.59
	GLSLR International	-12.80	-16.53	-26.74	-73.91	-79.25	-4.28	-15.99	-70.07	-76.21
	Arctic International	-5.71	-37.14	-37.14	-74.29	-82.86	-33.33	-33.33	-72.73	-81.82
	Arctic Domestic	7.93	-30.49	-21.34	-91.46	-94.51	-35.59	-27.12	-92.09	-94.92
Harmful Phytoplankton	All Shipping Pathways	-2.32	-10.97	-14.37	-69.75	-69.64	-8.85	-12.33	-69.03	-68.92
	Pacific International	-2.93	-11.49	-14.86	-69.97	-70.95	-8.82	-12.30	-69.06	-70.07
	Atlantic International	-1.77	-11.82	-14.40	-70.31	-72.21	-10.24	-12.86	-69.78	-71.72
	GLSLR International	-20.57	-19.43	-38.86	-65.14	-74.29	1.44	-23.02	-56.12	-67.63
	Arctic International	-1.66	-28.22	-31.12	-85.06	-85.89	-27.00	-29.96	-84.81	-85.65
	Arctic Domestic	13.97	-25.00	-13.97	-80.88	-85.29	-34.19	-24.52	-83.23	-87.10

Table A.2. Percentage change in NTOI of each of the management scenarios compared to no management. The relevant data is presented for both zooplankton NIS and harmful phytoplankton for each port salinity pair, when all shipping pathways are combined. The management scenarios where all and half of the transits are applied with the IMO D-2 standard are denoted by 100% and 50%, respectively. A limit of 100 million NTOI was applied to obtain percentage change values when NTOI was infinite.

		Freshwater Recipient Port			**Brackish Recipient Port**			**Marine Recipient Port**		
Taxonomic Group	**Management Scenarios**	Freshwater Source Port	Brackish Source Port	Marine Source Port	Freshwater Source Port	Brackish Source Port	Marine Source Port	Freshwater Source Port	Brackish Source Port	Marine Source Port
Zooplankton NIS	Exchange-Only to No-Management	-66.17	-65.85	22.39	-34.10	-40.99	11.42	-34.10	-8.99	-16.87
	Treatment-Only (50%) to No-Management	-44.29	-45.45	-43.02	-57.23	-50.18	-48.10	-57.23	-50.38	-48.01
	Exchange Plus Treatment (50%) to No-Management	-81.25	-81.37	-29.88	-75.14	-73.50	-46.71	-75.14	-53.57	-57.23
	Treatment-Only (100%) to No-Management	-87.14	-87.86	-89.10	-98.84	-99.29	-98.27	-98.84	-98.20	-97.04
	Exchange Plus Treatment (100%) to No-Management	-95.43	-96.21	-85.92	-99.42	-100.00	-96.89	-99.42	-98.43	-97.49
Harmful Phytoplankton	Exchange-Only to No-Management	-72.20	-59.00	24.73	-36.05	-41.14	9.37	-36.05	-8.77	-18.56
	Treatment-Only (50%) to No-Management	-38.35	-42.14	-44.27	-45.12	-49.26	-47.06	-45.12	-45.10	-45.02
	Exchange Plus Treatment (50%) to No-Management	-83.41	-76.57	-32.44	-68.37	-71.85	-38.79	-68.37	-50.63	-55.19
	Treatment-Only (100%) to No-Management	-83.85	-85.71	-84.95	-89.53	-89.58	-90.07	-89.53	-90.08	-90.43
	Exchange Plus Treatment (100%) to No-Management	-94.73	-94.71	-81.18	-93.02	-94.86	-88.42	-93.02	-91.52	-92.44

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