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Science Response 2019/030

THE RISKS OF SPREADING AQUATIC INVASIVE SPECIES TO CANADA BY MOVING UNMANAGED BALLAST WATER FROM CANADA TO THE U.S. WITHIN THE GREAT LAKES REGION

Context

Ballast water is a high-risk vector for the introduction and spread of harmful aquatic organisms and pathogens, also known as aquatic invasive species (AIS). Canada is a signatory to the International Maritime Organization's 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments (hereafter known as the Convention), which entered into force in 2017. Transport Canada proposed new ballast water regulations to give effect to this Convention in Canada and to mitigate the risk of introducing and spreading AIS. The proposed regulations would require any ballast water being loaded or discharged in Canadian waters to be managed as per the Convention (Canadian Gazette 2019). However, the United States (U.S.) exempts Great Lakes vessels (hereafter known as Lakers) from managing their ballast water. This discrepancy raised questions concerning U.S. Lakers loading ballast water in Canada and releasing it unmanaged into waters under U.S. jurisdiction, as these actions may present risks to Canada. Therefore, Transport Canada is seeking scientific advice from Fisheries and Oceans Canada on the risks of spreading AIS to new locations in Canada by moving unmanaged ballast water in commercial vessels from Canada to the U.S. within the Laurentian Great Lakes region (hereafter the Great Lakes). This advice is provided by synthesizing relevant scientific literature on the risks of spreading AIS in the Great Lakes via ballast water as a vector, including specific risks to Canada due to unmanaged ballast water, the effectiveness of onboard ballast water management systems (BWMS), and the risks of natural and anthropogenic vectors or pathways that may also spread AIS from the U.S. to Canada.

This Science Response Report results from the Science Response Process of June 19, 2019, on The risks to Canada by moving unmanaged ballast water from Canada to the United States within the Great Lakes.

Analysis and Response

Risks of spreading AIS via ballast water in the Great Lakes

The movement of unmanaged ballast water by Lakers within the Great Lakes region is a high-risk pathway for spreading AIS. Lakers transport the vast majority (95%) of ballast water moved within the Great Lakes, forming a highly interconnected network of ports and transporting an immense volume of ballast water annually (≥68 million tonnes), with a net inter-lake transport of ballast water from the lower to upper Great Lakes (e.g., Lake Erie to Lake Superior; Rup et al. 2010). The upstream inter-lake transport of AIS via ballast water is of concern because the waterways interconnecting the Great Lakes have a unidirectional downstream flow that impedes the upstream natural dispersal of species via water currents. The vast majority of organisms in ballast water are sessile or have low mobility, such as zooplankton (e.g., Mollusca larvae, rotifers, Copepoda, Cladocera; Briski et al. 2012, Adebayo et al. 2014) and phytoplankton (e.g., cyanobacteria, diatoms, dinoflagellates; Doblin et al. 2007, Klein et al. 2009, Casas-Monroy et al. 2012, Roy et al. 2012); these are organisms that would have difficulty to naturally disperse long distances upstream without human assistance. Doblin et al. (2007) provided evidence of upstream inter-lake transport of harmful aquatic species, having observed cyanobacterial algal bloom species in ballast water being transported from the lower Great Lakes to uninfected ports in the upper Great Lakes. Therefore, the inter-lake movement of ballast water from the lower to upper Great Lakes can rapidly transport species across long distances to regions difficult to reach by natural dispersal alone (Doblin et al. 2007, Rup et al. 2010). In general, the movement of any unmanaged ballast water within the Great Lakes is risky – including the transport of ballast water to downstream lakes, which can accelerate downstream dispersal to connection hubs – but the focus of this report is upstream inter-lake movement of ballast water, since this risk outweighs other movements of ballast water.

Lakers can spread AIS initially introduced to the Great Lakes through any pathway, such as transoceanic shipping. Examples of such AIS include Quagga Mussel (*Dreissena bugensis*), Zebra Mussel (*Dreissena polymorpha*), Spiny Water Flea (*Bythotrephes longimanus*), and Fishhook Water Flea (*Cercopagis pengoi*; Briski et al. 2012). Furthermore, the spread of Round Goby (*Neogobius melanostomus*) and Eurasian Ruffe (*Gymnocephalus cernua*) correspond to shipping activity in the Great Lakes (Pratt et al. 1992, Stepien et al. 1998, Bowen and Keppner 2015, Johansson et al. 2018), indicating that ballast water operations of Lakers contribute to the spread of AIS. Lakers can also facilitate the dispersal of native Great Lakes species outside their historical range, contributing to the homogenization of ecologically distinct communities (Briski et al. 2012). Lastly, the movement of ballast water by Lakers is a risky pathway, as ballast water from the Great Lakes can contain high abundances of nonindigenous zooplankton (Briski et al. 2012), and the survival rate of species is typically higher on short voyages (Wonham et al. 2001, Cordell et al. 2009, Chan et al. 2015), a characteristic of the transits within the Great Lakes (<24 hours for intra-lake transits and 3-4 days on average for inter-lake transits; Rup et al. 2010).

The spread of AIS through the ballast water operations of Lakers can hinder AIS management initiatives and increase ecological and socio-economic impacts of AIS in the Great Lakes. Detecting the arrival of AIS is a critical component of AIS management because the feasibility of eradicating or containing AIS decreases as they spread from their initial location of establishment (Locke et al. 2011). However, the rapid spread of AIS by ballast water over long distances in the Great Lakes reduces the window for effective management response. Another consequence of spreading AIS through ballast water is that it increases negative impacts, as with larger geographic spread, AIS adversely affect more human and ecological communities and require greater allocation of limited resources to manage their populations or impacts (Mack et al. 2000, Kolar and Lodge 2002, Colautti et al. 2006). For example, the economic cost due to Zebra Mussel and Quagga Mussel fouling – two widespread and highly invasive species – on equipment used by power generation and water treatment facilities throughout Southern Ontario has been estimated to be ~$8 million per year (Colautti et al. 2006). Therefore, preventing AIS from spreading through ballast water could lengthen the window of time to detect AIS when management response is the most effective and reduce the geographic area impacted by these species in the Great Lakes region.

Benefits and limitations of utilizing BWMS on Great Lakes vessels

The Convention's ballast water performance standard – Regulation D-2 – reduces the risk of species establishment by setting limits on the concentration of organisms in discharged ballast water. Compliance with the performance standard by vessels operating exclusively in the Great Lakes is predicted to substantially reduce the invasion risk for nonindigenous zooplankton (Casas-Monroy et al. 2014). On the other hand, model results indicated a low relative invasion risk for nonindigenous phytoplankton when ballast water was not managed, and the modelled effect of the D-2 standard did not reduce the expected risk of this taxonomic group (Casas-Monroy et al. 2014). However, the risk of nonindigenous phytoplankton may have been underestimated, as a very small number of Laker ballast water samples were analyzed for these species. Furthermore, this result does not represent the overall invasion risk of phytoplankton moved by Lakers or the effectiveness of the D-2 standard at mitigating this risk since other relevant phytoplankton taxa (i.e., harmful species rather than nonindigenous species) present additional risks that were not considered in this study.

The most feasible method for Lakers to adhere to the D-2 standard is by utilizing onboard BWMS. Most BWMS utilize a filtration process (e.g., screen or disc filters) followed by one or more disinfection processes, such as ultraviolet (UV) radiation or chlorination (Mouawad Consulting 2013), and studies have demonstrated that a variety of BWMS can substantially reduce the abundance of aquatic organisms in ballast water (Gregg et al., 2009). It is important to note that BWMS may not eliminate all organisms in ballast water, but can significantly reduce organism abundance (Paolucci et al. 2015). For example, certain life stages may be resistant to some treatment processes; Zebra Mussel can close their shell to avoid exposure to chemical treatment (de Lafontaine et al. 2009), and dinoflagellate cysts may be resistant to UV radiation treatment (Gregg et al. 2009).

The optimal conditions for BWMS are clear, temperate waters, while some Great Lakes ports may present unique challenges due to cold, turbid waters; certain chemical treatments such as electro-chlorination require water to be at least 15˚C in order to function properly (and also require sufficient chloride ions in the water to generate chlorine), filtration systems may need to be heated to prevent ice buildup (STX Canada Marine 2015), the effectiveness of UV radiation treatment is reduced when treating turbid water (Briski et al. 2013), and high amounts of filamentous algae may block filtration systems (Cangelosi et al. 2011). Furthermore, the relatively short transit routes between Great Lakes ports limit the use of certain treatment technologies with required retention times, such as chemical treatments that need to be retained for 1-2 days in order to be effective or before ballast water is safe to discharge into the environment (Mouawad Consulting 2013). Regardless of these challenges, certain BWMS are feasible for treating ballast water within the Great Lakes (Mouawad Consulting 2013, STX Canada Marine 2015). Casas-Monroy et al. (2018) determined that BWMS utilizing filtration plus UV radiation can effectively reduce the concentration of zooplankton and phytoplankton in water from Hamilton Harbour. It is expected that the performance of BWMS will improve in the future with advancements in treatment technologies. Overall, the evidence supports the conclusion that BWMS can greatly reduce the abundance of organisms in ballast water, mitigating the risk of spreading AIS by Lakers.

Risks to Canada by moving unmanaged ballast water from Canada to the U.S.

Lakers travelling from Canada to the U.S. can facilitate the spread of AIS, as these routes comprise a considerable volume of outbound shipping traffic from Canadian ports; from 2005-2007, ~15% (or 2170 trips) of outbound transits from Canadian Great Lakes and St. Lawrence River ports were to U.S. Great Lakes ports (Rup et al. 2010). Furthermore, the vast majority of these transits (~69% or 1508 trips) were to U.S. recipient ports in an upstream lake, and many of these transits were across very long distances (e.g., 295 trips from Canadian ports in Lake Erie to U.S. ports in Lake Superior; Rup et al. 2010). Utilizing BWMS on these voyages would help to mitigate the risk of dispersing AIS, as the movement of unmanaged ballast water on these transits can facilitate the establishment of AIS in U.S. ballast recipient ports (Figure 1). These species may then spread to connected U.S. ports in the region because Lakers travelling in U.S. waters are not required to manage their ballast water. Additional satellite populations of AIS will expedite spread by natural and human-assisted vectors and pathways, including water currents (Beletsky et al. 2017), animals (e.g., fish, waterbirds; Makarewicz et al. 2001, Kerfoot et al. 2011), and recreational boating (Drake et al. 2017), increasing the risk of spreading harmful species from the U.S. to Canada, outside of their existing distribution. It is recognized that other methods of dispersal may spread AIS from the U.S. to Canada (e.g., live bait trade), but the extent of such methods are unknown (see next section). Note that species may spread back to Canada via direct or indirect routes, using one or more pathways or connections to reach Canada.

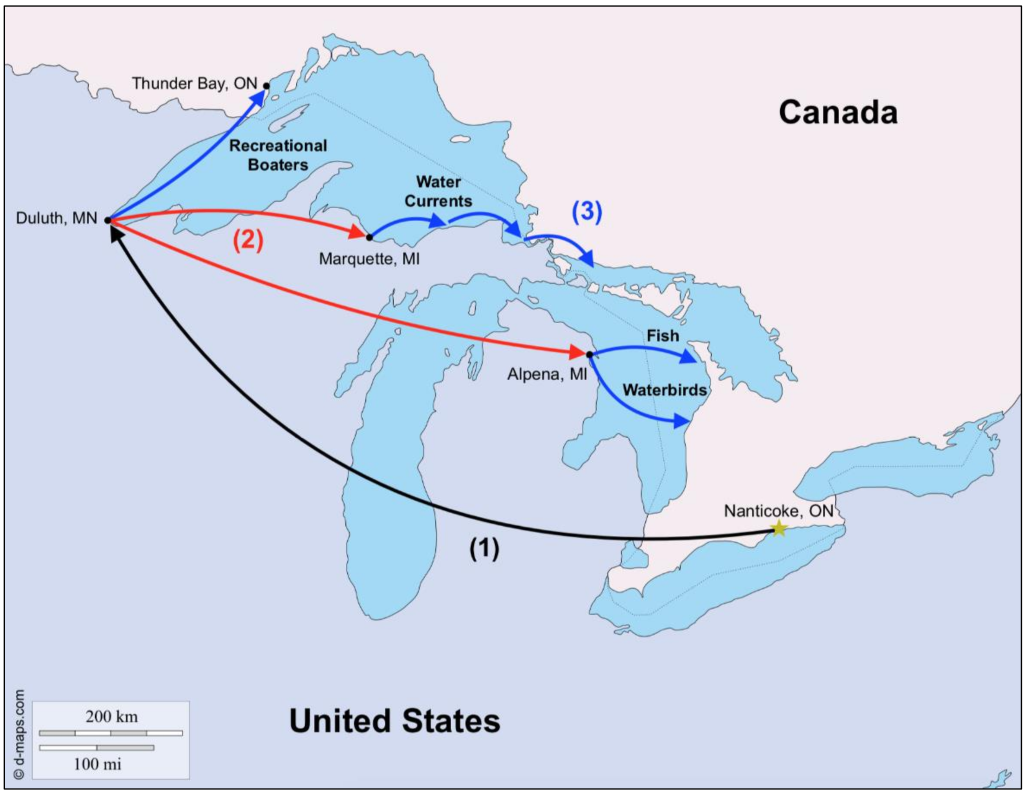

Figure 1. Illustration of potential pathways that may disperse AIS from the U.S. to Canada. The sequence of events are as follows: 1) Lakers transport unmanaged ballast water containing AIS from Canada to the U.S.; 2) these species rapidly spread to other U.S. Great Lakes ports since U.S. Lakers are exempt from managing their ballast water, resulting in the establishment of additional satellite populations; 3) the satellite populations can then become new sources for dispersal via water currents, birds, fish, and recreational boaters, accelerating their spread in the Great Lakes and into new locations in Canada.

Natural and anthropogenic vectors and pathways that may spread AIS from the U.S. to Canada

Water currents are the primary natural dispersal method for many aquatic species that have limited mobility or are non-mobile (e.g., the distribution of harmful algae blooms can be dependent on water currents; Qin et al. 2009, Carmichael and Boyer 2016). Due to the overall unidirectional water flow of the waterways interconnecting the Great Lakes, drifting organisms are much more likely to disperse downstream rather than upstream (Sun et al. 2013), and the downstream dispersal of drifting organisms in certain rivers can be rapid (the residence time for plankton in the Niagara River is 11-28 hours; Rozon et al. 2016). Therefore, if an AIS is spread via ballast water from a Canadian port to a U.S. port in an upstream lake (e.g., Lake Erie to Lake Huron), the species could then drift downstream and establish populations beyond its initial range in Canadian waters. For example, Beletsky et al. (2017) predicted that if Golden Mussel (*Limnoperna fortunei*) larvae were released in the Detroit River in Detroit, MI, they would drift downstream and have a high probability of settlement in the middle of the Western Basin of Lake Erie, including areas within Canada's jurisdiction. Additionally, Currie et al. (2017) modelled the spread of Grass Carp (*Ctenopharyngodon Idella*) in the Great Lakes, originating at the southern basin of Lake Michigan and the Maumee River in the western basin of Lake Erie. Their model results indicated that water currents are a very important driver of dispersal between basins, and Grass Carp dispersed much more rapidly to the downstream lakes than those lakes upstream.

Intra-lake currents can also disperse AIS from the U.S. to Canada within a given lake. For example, Zebra Mussel rapidly spread throughout Lake Erie within three years (1986-1988), likely due to natural dispersal of larvae and juveniles via lake currents (Griffiths et al. 1991, Carlton 2008). Studies on the influence of water flow on the dispersal of organisms in Lake Michigan illustrate that lake currents can rapidly disperse propagules across the lake. Rowe et al. (2015) mapped the spread of Zebra Mussel and Quagga Mussel in Lake Michigan through time (see Rowe et al. 2015, figure 4 for details), where lake currents likely played a significant role in their dispersal in addition to anthropogenic-assisted dispersal via commercial shipping (Johnson and Carlton 1996, Beletsky et al. 2017). Additionally, modelling by Beletsky et al. (2007) suggests that fish larvae could disperse from the southwestern end of Lake Michigan to the northern basin within three months during years with strong northward currents along the east coast. Although the extent and rate of AIS dispersal via currents varies greatly depending on the specific flow regime of each lake, location of propagule release, water flow of a particular year or season, and the species' life history traits (Beletsky et al. 2017, Drake et al. 2017), these studies demonstrate that water currents can significantly contribute to the intra-lake and downstream dispersal of AIS, and illustrate the importance of preventing the upstream human-mediated spread of AIS in the Great Lakes.

Another natural dispersal mechanism that may spread AIS back to Canada from the U.S. is internal or external transportation via vectors such as fish and waterbirds. Internal transport of AIS by animals following ingestion can occur when propagules tolerate gut passage and hatch upon defecation (Jarnagin et al. 2000, Charalambidou et al. 2003). The extent of dispersal is highly species-specific as it depends on several factors, including the selectivity of animals for certain prey (influencing the number of AIS propagules transported; Jarnagin et al. 2000), the distance travelled by animals between consumption and defecation, and the tolerance of propagules to gut passage (e.g., smaller seeds or thick-shelled eggs are better adapted to gut passage; Charalambidou et al. 2003, Reynolds et al. 2015). External transport by animals can occur when AIS or their propagules become attached to animals, such as on the feet or feathers of waterbirds, and the extent of propagule dispersal depends on their ability to attach to animals, the desiccation tolerance of propagules, and the movement patterns of animals (Green 2015, Reynolds et al. 2015). Trials cited by Makarewicz et al. (2001) confirmed that Fishhook Water Flea in Lake Ontario can foul the plumage of diving ducks, potentially contributing to their short-distance dispersal to adjunct waterbodies. Overall, the dispersal of AIS via animals is relatively poorly studied in the Great Lakes. However, Kerfoot et al. (2011) suggests that internal transport by fish may explain the near-shore to off-shore transport of Spiny Water Flea in Lake Michigan. In addition, Figuerola et al. (2005) determined that the migration routes of waterfowl explain the genetic variation in invertebrate populations in North America, indicating that animals may play an important role in AIS propagule dispersal. Even though the cross-border dispersal of AIS via animals is unquantified in the Great Lakes, it is a viable possible pathway for spreading AIS back to Canada.

Recreational boating is a high-risk pathway for the introduction and spread of AIS in the Great Lakes either by trailering boats overland or boating on the water. Although the relative invasion risk of each recreational boater is very small, recreational boating as a pathway is risky due to the high volume of boating activity in the Great Lakes region (~11 million trips annually; Drake et al. 2017). For example, Johnson et al. (2001) predicted that 170 overland Zebra Mussel dispersal events could occur annually from a public boat launch on Lake St. Clair in Michigan, and Buchan and Padilla (1999) found a correlation between the pattern of recreational boating activity and the establishment of Zebra Mussel in inland lakes in Wisconsin. There are numerous ways that AIS may be transported by recreational boaters and anglers depending on their life history and character traits, as detailed below. Live wells and engine cooling water can become contaminated with small aquatic organisms (e.g., Spiny Water Flea, Zebra Mussel larvae, etc.), and are especially risky because ambient water is used for this equipment, resulting in the concentration of organisms to be the same as in the surrounding water (Johnson et al. 2001, Drake et al. 2017). Bilge water can also accumulate aquatic organisms (Kelly et al. 2013), but is considered less risky than live wells since it typically has ~10 times less the concentration of organisms than the surrounding water (Johnson et al. 2001, Drake et al. 2017). Additionally, certain AIS can accumulate on boating and fishing equipment (e.g., Fishhook Water Flea can accumulate on fishing lines; Jacobs and MacIsaac 2007, Kelly et al. 2013). Lastly, AIS may become directly or indirectly attached to the external surfaces of boats or trailers; Zebra Mussel can foul boat hulls (Minchin et al. 2003, Collas et al. 2016, Ventura et al. 2016), and aquatic invasive plants or plants carrying AIS can become entangled in boats and trailers (Johnson et al. 2001). Although the role of recreational boating in AIS dispersal has been studied relatively well in the Great Lakes (Johnson et al. 2001, MacIsaac et al. 2004, Muirhead and MacIsaac 2005, Kelly et al. 2013, Drake et al. 2017), the cross-border movement of recreational boaters is currently unquantified, but can be considered a possible viable pathway presenting a risk to Canada.

Significance of ballast water as a vector given other methods of AIS dispersal in the Great Lakes

Overall, the movement of ballast water spreads AIS at a much faster rate than natural dispersal alone, as it can rapidly transport species long distances and across unfavorable environments. Hebert and Cristescu (2002) estimated that human-mediated dispersal of Water Fleas (Cladocera) from Europe to North America is 50,000 times greater than natural background rates. Additionally, Sieracki et al. (2014) estimated that without human assistance, it would have taken more than 20 times longer for Zebra Mussel to reach their 1992 distribution, and approximately twice as long for Eurasian Ruffe to reach their 2014 distribution in the Great Lakes region.

Although the unidirectional flow of the waterways interconnecting the Great Lakes inhibits the inter-lake upstream dispersal of AIS via water currents, AIS may be able to naturally disperse upstream using other dispersal mechanisms, depending on the character traits of a given species; highly mobile AIS such as fish may be able to swim upstream unaided, or AIS propagules may be transported by mobile animals such as fish or waterbirds. Some invasive fish species such as Alewife (*Alosa pseudoharengus*) and Sea Lamprey (*Petromyzon marinus*) may have used the artificial waterways (canals and shipping locks) interconnecting the Great Lakes to gain access to upstream lakes (Smith and Tibbles 1980, Alexander 2009, Mandrak and Cudmore 2010). However, Kim and Mandrak (2016) observed only a small percentage (3.9%) of tagged fish moving through the Welland Canal to enter either Lake Ontario or Lake Erie, indicating that the system of locks limits the rate of dispersal of highly mobile species. Therefore, natural dispersal within a lake or to downstream lakes may occur relatively rapidly, but inter-lake upstream dispersal is likely to be slower due to the difficulties travelling through shipping locks and overcoming strong water currents in rivers (Drake et al. 2017), highlighting the risk of moving unmanaged ballast water to upstream lakes.

As previously described, recreational boats are high-risk vectors for the spread of AIS (Drake et al. 2017). However, both Canada and the U.S. put considerable effort into preventing the spread of AIS through recreational boating in the Great Lakes by conducting scientific research, raising public awareness, facilitating public educational opportunities, and implementing watercraft washing and inspection stations. These efforts to mitigate the risks of recreational boating would be undermined if ballast water is not similarly managed effectively. Additionally, it is important to note that ballast water likely spreads AIS at a faster rate since commercial vessels travel longer distances and move a much larger volume of water (propagules) than do recreational boats. Drake et al. (2015) estimated that it would take one year on average for a highly invasive species to invade at least one port in Lake Superior from Lake Erie via ballast water, whereas it would take 7.64 years on average to do so by recreational boating on the water (Drake et al. 2017).

Conclusions

Out of all the pathways that may spread AIS in the Great Lakes, the movement of unmanaged ballast water is considered the highest risk pathway due to the enormous volume of water transported by commercial ships across long distances to upstream lakes. However, the risk of spreading AIS through ballast water can be greatly reduced when ships manage ballast water using a BWMS. Therefore, the management of ballast water on commercial vessels operating within Canadian jurisdiction in the Great Lakes would strongly protect Canadian aquatic ecosystems from the dispersal of AIS. This includes vessels travelling outbound with ballast water, from Canada to the U.S., as AIS transported in unmanaged ballast water on these transits may become established in upstream recipient U.S. ports. These species may rapidly spread further across the Great Lakes in the U.S. due to the transfer of unmanaged ballast water between U.S. Great Lakes ports. The additional satellite populations can then become sources for propagule dispersal via water currents, animal vectors, and recreational boating, accelerating the range expansion of AIS in the Great Lakes and in Canada. Permitting the movement of unmanaged ballast on transits from Canada to the U.S. can have larger than expected consequences due to the multiple possible alternate pathways for dispersal back to Canada. Accelerated dispersal of AIS in this way reduces Canada’s ability to effectively respond to the arrival of AIS, increasing negative impacts on Canadian ecosystems and society.

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Sources of Information

Adebayo, A. A., Zhan, A., Bailey, S. A., and MacIsaac, H. J. 2014. Domestic ships as a potential pathway of nonindigenous species from the Saint Lawrence River to the Great Lakes. Biological Invasions 16(4): 793-801.

Alexander, J. 2009. *Pandora's Locks: The Opening of the Great Lakes-St. Lawrence Seaway*. Michigan State University Press.

Beletsky, D., Mason, D. M., Schwab, D. J., Rutherford, E. S., Janssen, J., Clapp, D. F., and Dettmers, J. M. 2007. Biophysical Model of Larval Yellow Perch Advection and Settlement in Lake Michigan. J. Great Lakes Res. 33(4): 842-866.

Beletsky, D., Beletsky, R., Rutherford, E. S., Sieracki, J. L., Bossenbroek, J. M., Chadderton, W. L., Wittmann, M. E., Annis, G. M., and Lodge, D. M. 2017. Predicting spread of aquatic invasive species by lake currents. J. Great Lakes Res. 43(3): 14-32.

Bowen, A., and Keppner, S. 2015. Surveillance for Ruffe in the Great Lakes, 2015. U.S. Fish and Wildlife Service. 48 pp.

Briski, E., Wiley, C. J., and Bailey, S. A. 2012. Role of domestic shipping in the introduction or secondary spread of nonindigenous species: Biological invasions within the Laurentian Great Lakes. J. Appl. Ecol. 49(5): 1124-1130.

Briski, E., Allinger, L. E., Balcer, M., Cangelosi, A., Fanberg, L., Markee, T. P., Mays, N., Polkinghorne, C. N., Prihoda, K. R., Reavie, E. D., Regan, D. H., Reid, D. H., Saillard, H. J., Schwerdt, T., Schaefer, H., TenEyck, M., Wiley, C. J., and Bailey, S. A. 2013. Multidimensional approach to invasive species prevention. Environmental Science & Technology 47: 1216-1221.

Buchan, L. A., and Padilla, D. K. 1999. Estimating the probability of long-distance overland dispersal of invading aquatic species. Ecological Applications 9(1): 254.

Canadian Gazette. 2019. Ballast water regulations. Part 1, Volume 153, Number 23. (Accessed June 30, 2019).

Cangelosi, A., Allinger, L., Balcer, M., Mays, N., Markee, T., Polkinghorne, C., Prihoda, K., Reavie, E., Reid, D., Saillard, H., Schwerdt, T., Schaefer, H., and TenEyck, M. 2011. Final report of the land-based, freshwater testing of the AlfaWall AB PureBallast® ballast water treatment system. Great Ships Initiative, Northeast-Midwest Institute, Washington, DC. pp 94.

Carlton, J. T. 2008. The Zebra Mussel Dreissena polymorpha Found in North America in 1986 and 1987. J. Great Lakes Res. 34(4): 770-773.

Carmichael, W. W., and Boyer, G. L. 2016. Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes. Harmful Algae 54: 194-212.

Casas-Monroy, O., Roy, S., and Rochon, A. 2012. Dinoflagellate cysts in ballast sediments: Differences between Canadas east coast, west coast and the Great Lakes. Aquatic Conservation: Marine and Freshwater Ecosystems 23(2): 254-276.

Casas-Monroy, O., Linley, R.D., Adams, J.K., Chan, F.T., Drake, D.A.R., and Bailey, S.A. 2014. National risk assessment for introduction of aquatic nonindigenous species to Canada by ballast water. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/128. pp vi + 73.

Casas-Monroy, O., Linley, R. D., Chan, P., Kydd, J., Byllaardt, J. V., and Bailey, S. 2018. Evaluating efficacy of filtration UV-C radiation for ballast water treatment at different temperatures. J. Sea Res. 133: 20-28.

Chan, F. T., Bradie, J., Briski, E., Bailey, S. A., Simard, N., MacIsaac H. J. 2015. Assessing introduction risk using species' rank-abundance distributions. Proc. R. Soc. B 282: 20141517.

Charalambidou, I., Ketelaars, H. A., and Santamaria, L. 2003. Endozoochory by ducks: Influence of developmental stage of Bythotrephes diapause eggs on dispersal probability. Diversity Distributions 9(5): 367-374.

Colautti, R. I., Bailey, S. A., Overdijk, C. D., Amundsen, K., and MacIsaac, H. J. 2006. Characterised and projected costs of nonindigenous species in Canada. Biological Invasions 8(1): 45-59.

Collas, F. P., Karatayev, A. Y., Burlakova, L. E., and Leuven, R. S. 2016. Detachment rates of dreissenid mussels after boat hull-mediated overland dispersal. Hydrobiologia 810(1): 77-84.

Cordell, J. R., Lawrence, D. J., Ferm, N. C., Tear, L. M., Smith, S. S., and Herwig, R. P. 2009. Factors influencing densities of non-indigenous species in the ballast water of ships arriving at ports in Puget Sound, Washington, United States. Aquatic Conserv: Mar. Freshw. Ecosyst. 19(3): 322-343.

Currie, W. J. S., Kim, J., Koops, M. A., Mandrak, N. E., O'Connor, L. M., Pratt, T. C., Timusk, E., and Choy, M. 2017. Modelling spread and assessing movement of Grass Carp, Ctenopharyngodon idella, in the Great Lakes basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/114. v + 31 p.

de Lafontaine, Y., Despatie, S., Veilleux, É, and Wiley, C. 2009. Onboard ship evaluation of the effectiveness and the potential environmental effects of PERACLEAN® Ocean for ballast water treatment in very cold conditions. Environmental Toxicology 24: 49-65.

Doblin, M. A., Coyne, K. J., Rinta-Kanto, J. M., Wilhelm, S. W., and Dobbs, F. C. 2007. Dynamics and short-term survival of toxic cyanobacteria species in ballast water from NOBOB vessels transiting the Great Lakes—implications for HAB invasions. Harmful Algae 6(4): 519-530.

Drake, D. A. R., Bailey, S. A., and Mandrak, N. E. 2015. Predicting the secondary spread of aquatic invasive species through ballast water and recreational boating in the Great Lakes Basin. Completion report submitted to the Fishery Research Program of the Great Lakes Fishery Commission. Sept. 30, 2015. 45p.

Drake, D. A. R., Bailey, S. A., and Mandrak, N. E. 2017. Ecological risk assessment of recreational boating as a pathway for the secondary spread of aquatic invasive species in the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/030. v + 85 p.

Figuerola, J., Green, A. J., and Michot, T. C. 2005. Invertebrate eggs can fly: Evidence of waterfowl-mediated gene flow in aquatic invertebrates. The American Naturalist 165(2): 274.

Green, A. J. 2015. The importance of waterbirds as an overlooked pathway of invasion for alien species. Diversity and Distributions 22(2): 239-247.

Gregg, M., Rigby, R., and Hallegraeff, G. 2009. Review of two decades of progress in the development of management options for reducing or eradicating phytoplankton, zooplankton and bacteria in ships ballast water. Aquatic Invasions 4(3): 521-565.

Griffiths, R. W., Schloesser, D. W., Leach, J. H., and Kovalak, W. P. 1991. Distribution and dispersal of the Zebra Mussel (*Dreissena polymorpha*) in the Great Lakes Region. Can. J. Fish. Aquat. Sci. 48(8): 1381-1388.

Hebert, P. D., and Cristescu, M. E. 2002. Genetic perspectives on invasions: The case of the Cladocera. Can J. Fish. Aquat. Sci. 59(7): 1229-1234.

Jacobs, M. J., and MacIsaac, H. J. 2007. Fouling of fishing line by the waterflea *Cercopagis pengoi*: A mechanism of human-mediated dispersal of zooplankton? Hydrobiologia 583(1): 119-126.

Jarnagin, S. T., Swan, B. K., and Kerfoot, W. C. 2000. Fish as vectors in the dispersal of *Bythotrephes cederstroemi*: Diapausing eggs survive passage through the gut. Freshwater Biology 43(4): 579-589.

Johansson, M. L., Dufour, B. A., Wellband, K. W., Corkum, L. D., MacIsaac, H. J., and Heath, D. D. 2018. Human-mediated and natural dispersal of an invasive fish in the eastern Great Lakes. Heredity 120(6): 533-546.

Johnson, L. E., and Carlton, J. T. 1996. Post-establishment spread in large-scale invasions: Dispersal mechanisms of the Zebra Mussel *Dreissena polymorpha*. Ecology: 77(6): 1686-1690.

Johnson, L. E., Ricciardi, A., and Carlton, J. T. 2001. Overland dispersal of aquatic invasive species: A risk assessment of transient recreational boating. Ecological Applications 11(6): 1789–1799.

Kelly, N. E., Wantola, K., Weisz, E., and Yan, N. D. 2013. Recreational boats as a vector of secondary spread for aquatic invasive species and native crustacean zooplankton. Biological Invasions 15(3): 509-519.

Kerfoot, W. C., Yousef, F., Hobmeier, M. M., Maki, R. P., Jarnagin, S. T., and Churchill, J. H. 2011. Temperature, recreational fishing and diapause egg connections: Dispersal of spiny water fleas (*Bythotrephes longimanus*). Biological Invasions 13(11): 2513-2531.

Kim, J., and Mandrak, N. E. 2016. Assessing the potential movement of invasive fishes through the Welland Canal. J. Great Lakes Res. 42(5): 1102-1108.

Klein, G., Kaczmarska, I., and Ehrman, J. M. 2009. The diatom Chatoceros in ships' ballast waters-survivorship of stowaways. Acta Botanica Croatia 68(2): 325-338.

Kolar, C. S., and Lodge, D. M. 2002. Ecological Predictions and Risk Assessment for Alien Fishes in North America. Science 298(5596): 1233-1236.

Locke, A., Mandrak, N. E., and Therriault, T. W. 2011. A Canadian Rapid Response Framework for Aquatic Invasive Species. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/114. vi + 30 p.

MacIsaac, H. J., Borbely, J. V., Muirhead, J. R., and Graniero, P. A. 2004. Backcasting and forecasting biological invasions of inland lakes. Ecological Applications 14(3): 773-783.

Mack, R. N., Simberloff, D., Lonsdale, W. M., Evans, H., Clout, M., and Bazzaz, F. A. 2000. Biotic Invasions: Causes, Epidemiology, Global Consequences, and Control. Ecological Applications 10(3): 689-710.

Makarewicz, J. C., Grigorovich, I. A., Mills, E., Damaske, E., Cristescu, M. E., Pearsall, W., LaVoie, M. J., Keats, R., Rudstam, L., Hebert, P., Halbritter, H., Kelly, T., Matkovich, C., and Macisaac, H. J. 2001. Distribution, Fecundity, and Genetics of *Cercopagis pengoi* (Ostroumov) (Crustacea, Cladocera) in Lake Ontario. J. Great Lakes Res. 27(1): 19-32.

Mandrak, N. E., and Cudmore, B. 2010. The fall of Native Fishes and the rise of Non-native Fishes in the Great Lakes Basin. Aquatic Ecosystem Health & Management 13(3): 255-268.

Minchin, D., Maguire, C., and Rosell, R. 2003. The zebra mussel (*Dreissena polymorpha* Pallas) invades Ireland: human mediated vectors and the potential for rapid intranational dispersal. Biol. Environ.: Proc. R. Irish Acad. 103B: 23-30.

Mouawad Counsulting, 2013. Assessment of ballast water treatment processes and availability with respect to the Great Lakes and St. Lawrence Seaway System. In Transactions on ballast water treatment systems for the Great Lakes-St. Lawrence Seaway System. Report No. 2013-2-1-2, Revision No. 5, submitted to Transport Canada, Ottawa, ON. pp 21-86.

Muirhead, J. R., and MacIsaac, H. J. 2005. Development of inland lakes as hubs in an invasion network. J. Appl. Ecol. 42(1): 80-90.

Paolucci, E. M., Hernandez, M. R., Potapov, A., Lewis, M. A., and Macisaac, H. J. 2015. Hybrid system increases efficiency of ballast water treatment. J. Appl. Ecol. 52(2): 348-357.

Pratt, D. M., Blust, W. H., and Selgeby, J. H. 1992. Ruffe, *Gymnocephalus cernuus*: Newly Introduced in North America. Can. J. Fish Aquat. Sci. 49(8): 1616-1618.

Qin, B., Zhu, G., Gao, G., Zhang, Y., Li, W., Paerl, H. W., and Carmichael, W. W. 2009. A Drinking Water Crisis in Lake Taihu, China: Linkage to Climatic Variability and Lake Management. Environmental Management 45(1): 105-112.

Reynolds, C., Miranda, N. A., and Cumming, G. S. 2015. The role of waterbirds in the dispersal of aquatic alien and invasive species. Diversity and Distributions 21(7): 744-754.

Rowe, M. D., Obenour, D. R., Nalepa, T. F., Vanderploeg, H. A., Yousef, F., and Kerfoot, W. C. 2015. Mapping the spatial distribution of the biomass and filter-feeding effect of invasive dreissenid mussels on the winter-spring phytoplankton bloom in Lake Michigan. Freshwater Biology 60(11): 2270-2285.

Roy, S., Parenteau, M., Casas-Monroy, O., and Rochon, A. 2012. Coastal ship traffic: A significant introduction vector for potentially harmful dinoflagellates in eastern Canada. Can. J. Fish. Aquat. Sci. 69(4): 627-644.

Rozon, R. M., Bowen, K. L., Niblock, H. A., Fitzpatrick, M. A. J., and Currie, W.J.S. 2016. Assessment of the phytoplankton and zooplankton populations in the Niagara River (Canada) area of concern in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3184: iv + 66p.

Rup, M. P., Bailey, S. A., Wiley, C. J., Minton, M. S., Miller, A. W., Ruiz, G. M., and MacIsaac, H. J. 2010. Domestic ballast operations on the Great Lakes: Potential importance of Lakers as a vector for introduction and spread of nonindigenous species. Can. J. Fish. Aquat. Sci. 67(2): 256-268.

Sieracki, J. L., Bossenbroek, J. M., and Chadderton, W. L. 2014. A spatial modeling approach to predicting the secondary spread of invasive species due to ballast water discharge. PLoS ONE 9(12).

Smith, B. R., and Tibbles, J. J. 1980. Sea Lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan, and Superior: History of Invasion and Control, 1936–78. Can. J. Fish. Aquat. Sci. 37(11): 1780-1801.

Stepien, C. A., Dillon, A. K., and Chandler, M. D. 1998. Genetic identity, phylogeography, and systematics of Ruffe *Gymnocephalus* in the North American Great Lakes and Eurasia. J. Great Lakes Res. 24(2): 361-378.

STX Canada Marine, 2015. Assessing the feasibility of ballast water treatment system installation and operation on existing vessels on the Great Lakes and St. Lawrence River System. In Transactions on ballast water treatment systems for the Great Lakes-St. Lawrence Seaway System. Report No. 182-001-01, Revision No. 07, submitted to Transport Canada, Ottawa, ON. pp 87-380.

Sun, Y., Wells, M. G., Bailey, S. A., and Anderson, E. J. 2013. Physical dispersion and dilution of ballast water discharge in the St. Clair River: Implications for biological invasions. Water Resources Research 49(5): 2395-2407.

Ventura, L. D., Weissert, N., Tobias, R., Kopp, K., and Jokela, J. 2016. Overland transport of recreational boats as a spreading vector of zebra mussel *Dreissena polymorpha*. Biological Invasions 18(5): 1451-1466.

Wonham, M. J., Walton, W. C., Ruiz, G. M., Frese, A. M., and Galil, B. S. 2001. Going to the source: role of the invasion pathway in determining potential invaders. Marine Ecology Progress Series 215: 1-12.

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