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Relative risk assessment for ballast-mediated invasions at Canadian Arctic ports

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Abstract Vector-based risk assessment is a powerful and efficient management approach for nonindigenous species (NIS). By managing a vector, an entire assemblage of associated NIS is simultaneously considered. The majority of current risk assessment frameworks have been conducted for a single, or selected few, target species and thus are not useful for managing vectors transporting a large number of potentially unknown species. Here we develop a predictive framework to assess relative invasion risk for a vector (ballast water) transporting an unknown species assemblage, using the Canadian Arctic as a case study. Ballast water discharge is a known high-risk vector globally, but its magnitude in the Arctic has not been well characterized. Our framework determined relative invasion risks between different transit pathways by quantifying the probability of NIS successfully transiting all stages of the invasion process and the magnitude of consequences of introduction to those ports. Churchill, Manitoba was ranked at 'higher' invasion risk via ballast water discharged by international merchant vessels than any other recipient port studied. The overall pattern of ballast water discharge suggests that water originating from coastal domestic sources carried by international merchant vessels may be important for dispersal of NIS. In addition, ballast-mediated NIS are more likely to arrive to the Hudson Bay region during summer months. These results can be useful for developing prevention and early detection programs for the region. Our risk assessment framework is not limited to ballast water and could be applied to other vectors for effective management of NIS.

Keywords Arctic · Ballast water · Biological invasions · Climate change · Risk prediction · Vector management

Introduction

Globalization has increased international trade and transport networks, moving not only people and goods but also nonindigenous species (NIS) around the world (Hulme 2009). While some NIS are introduced intentionally as biocontrol agents or food, many are

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transported and released accidentally as contaminants or stowaways (Hulme et al. 2008). Given the ecological and economic harm that may result from NIS introductions, considerable effort has been invested in developing risk assessments to direct NIS prevention and control strategies.

In the context of biological invasions, risk assessments quantify the probability and consequence of NIS introduction events (Hayes 2003). The majority of risk assessments have been conducted for single (e.g., Stone et al. 1997; Bartell and Nair 2003; Therriault and Herborg 2007) or selected few target species (e.g., Pheloung et al. 1999; Kolar and Lodge 2002; Barry et al. 2008). A typical species-specific risk assessment estimates the probability that a NIS will successfully pass through all stages of the invasion process and characterizes the expected impact of the species in the recipient environment. Invasion stages include arrival, survival, establishment and spread, and may be evaluated individually before being combined into a final probability of successful introduction (Orr 2003). Completing a species-specific risk assessment requires extensive data on the invasion history, environmental requirements and biological traits of target species, as well as characteristics of the recipient environment. Risk assessments may be performed prior to the introduction of a NIS in an effort to manage or regulate activities that may lead to the introduction; alternatively, they may be conducted retrospectively so that limited resources can be most effectively allocated to control or eradicate NIS already introduced (Andersen et al. 2004).

Recently, there have been several proposals to move toward vector-based risk assessment as a strategy for managing NIS (e.g., Andow 2003; Ruiz and Carlton 2003; Hulme 2009). A vector is defined as the conveyance carrying species along a pathway, where the pathway is the geographic route between the source region and the release sites (Lockwood et al. 2005). There are multiple reasons to conduct vector-based rather than species-specific risk assessments. First, it is often impossible to predict which species may be accidentally introduced via broad-scale vectors, such as ballast water, shipping containers, and commercial imports (Andow 2003; Ruiz and Carlton 2003; National Research Council 2011). Second, biological and ecological data required for species-specific risk assessments are often limited even for priority high-risk NIS (Ruiz and Carlton 2003). Therefore, focusing efforts to characterize propagule pressure (i.e., the number of arrivals, the number of NIS propagules per arrival and the condition of the released propagules) and colonization pressure (i.e., the number of species) exerted by a transport vector to a given recipient area is a useful strategy for quantifying and predicting invasion risk (Colautti et al. 2006; Lockwood et al. 2009). In addition, results from vector-based risk assessments can be translated to vector management policies, such as the prohibition of high-risk species in the aquarium trade and mandatory ballast water exchange in international shipping (Andow 2003). By addressing the vector, the entire assemblage of NIS associated with it is simultaneously managed, providing a powerful and efficient management approach (Ruiz and Carlton 2003).

Ballast water is a major transport vector of a wide variety of aquatic NIS worldwide (Klein et al. 2010; DiBacco et al. 2011; Seiden et al. 2011; Briski et al. 2012). Very few studies, however, have examined the magnitude of the vector in the Arctic (e.g., McGee et al. 2006; Ruiz and Hewitt 2009), and only one has done so qualitatively for northern Canada (Niimi 2007). At first glance, the Arctic would appear an unlikely region for ship-mediated biological invasions. The extent of shipping to most northern ports is low relative to temperate and tropical locations, thereby constraining the transfer of NIS. In addition, low temperature and limited food resources may hinder survivorship, reproduction, and/or population growth of many species in the Arctic (Vermeij and Roopnarine 2008; Ruiz and Hewitt 2009). However, changes in temperature regimes, ocean currents, sea level, and other key physical processes associated with climate change are expected to profoundly influence species dispersal and survival (Vermeij and Roopnarine 2008; Hellmann et al. 2008; Ruiz and Hewitt 2009; Wassmann et al. 2010). For example, the Pacific diatom *Neodenticula seminae* was found in the North Atlantic Ocean for the first time since the Pleistocene (Reid et al. 2007). Evidence suggests that the species was likely carried by increased flows of Pacific water from the Bering Sea through the Arctic Ocean following recession of coastal ice sheets, however the possibility of ballast water transport could not be dismissed (Reid et al. 2007). Melting sea ice can facilitate human-mediated transport of NIS to the Arctic by opening new waterways and shipping channels in the Arctic Ocean as well as extending the length of the shipping season (Howell and Yackel 2004; Arctic Council 2009; Khon et al. 2010).

Once released in Arctic waters, NIS may benefit from enhanced survival associated with warmer climate and increased food supply (Vermeij and Roopnarine 2008; Cheung et al. 2009; Rooney and Paterson 2009).

Commercial vessels began to use the Northeast Passage and the Northern Sea Route in 2009 to dramatically reduce the time and cost to ship goods from northern Europe to northeast Asia and northwest North America (Khon et al. 2010). The Northwest Passage was free of pack ice and fully navigable in the summer of 2007, providing a direct shipping route between western Europe and eastern Asia for the first time in recorded history (Cressey 2007; Khon et al. 2010). Future development in the Arctic, including increased extraction of mineral and petroleum resources as well as expanded tourism and community development, will further increase exposure of Arctic ports to ship traffic and the potential for ballast-mediated invasions (Arctic Council 2009). Such changes in shipping activities, in combination with climate warming, will increase the potential for successful ballast-mediated invasions. Therefore, ballast water risk assessments are clearly needed for the region.

Here, we develop a framework to assess relative invasion risk for a vector transporting an unknown species assemblage, using ballast water transport in the Canadian Arctic as a case study. The objectives of the study are twofold: first, to characterize ballast water discharge patterns for different vessel pathways in the region and, second, to identify ports at relatively high risk of ballast-mediated invasions and the responsible vessel pathway. The principal goal of the study is to direct research and preventive management efforts at potentially high-risk sites and vessel pathways so that Arctic ecosystems can be protected from the negative effects that often accompany biological invasions.

Methods and materials

Our relative risk assessment adopts methods from species-specific assessments (Orr 2003; Therriault and Herborg 2007), with modifications to accommodate the suite of unidentified NIS potentially associated with the ballast water vector. First, the probability of introduction was estimated by combining the individual probabilities of successful arrival, survival and establishment, based on ballast water discharge data and environmental similarity between source and recipient ports. Second, the potential magnitude of consequence of the introduction was estimated based upon the number of high impact ballast-mediated NIS recorded for ecoregions of source ports. Finally, the probability of introduction and the potential magnitude of consequence were combined for a relative invasion risk rating.

Estimating probability of arrival

A comprehensive database of ballast water discharges at Canadian Arctic ports between 2005 and 2008 was assembled using Transport Canada's Ballast Water Database (TCBWD; https://wwwapps2.tc.gc.ca/saf-sec-sur/4/cpscs-scepc/default.asp, accessed March 2009) as the primary data source. The Canadian Arctic, as defined by Transport Canada, covers all Canadian waters north of 60° and those in Ungava Bay, Hudson Bay and James Bay (Fig. 1). All vessels with a ballast capacity greater than eight m^3 are required to submit ballast water reports prior to their first port-of-call in Canadian waters; we considered only merchant vessels for our study because other vessel types carry very little or no ballast water and do not consistently report ballast activities. Data self-reported by vessels to the TCBWD provides information on the ballast history for each vessel transit, including date, location and volume of ballast uptake and discharge events as well as any management activities. Our database was then supplemented with shipping data from the Canadian Coast Guard's Information System on Marine Navigation (INNAV). Canada requires all commercial vessels to report to INNAV when crossing into each Traffic Service Zone, while additional voluntary reporting regularly occurs for the duration of the transit for safety reasons. Information reported to INNAV includes arrival and departure events, and cargo and ballast operations at ports (in binary format; volumes are not reported), and all reports are date and time coded. We grouped vessels in the dataset into two pathways according to operation region: 'international' vessels that operated outside of the Canadian exclusive economic zone (EEZ) for at least part of the study period; and 'coastal domestic' vessels that transited outside the Canadian Arctic but operated exclusively within Canada's EEZ for the entire study period. There were no 'Arctic' vessels that operated exclusively within the Canadian Arctic for the entire study period.

Gaps in ballast water data existed for 26 coastal domestic vessels because vessels operating entirely within Canadian waters are not required to submit ballast water reports. Through industry contacts, we recovered ballast records for six of the 26 vessels. Remaining data gaps for 20 vessels, representing 639 of 1,161 total merchant transits, were filled in using cargo information in the INNAV database. Based on the established relationship between cargo and ballast water operations in commercial vessels (Rup et al. 2010; David et al. 2012), we assumed that vessels discharged ballast water if cargo was loaded, resulting in 77 transits with ballast water discharge. Consultation with the shipping industry confirmed low frequency of ballast water discharges by vessels transporting supplies to Northern communities (i.e., annual sealift); since the vessels were generally fully laden with cargo, they carried very little or no ballast water during transits to Arctic ports. We estimated discharge volumes for 50 of these transits using the historical median discharge volume previously reported by the same vessel on non-Arctic transits, since Rup et al. (2010) demonstrated that a single vessel carries a typical volume of ballast water on 90 % of domestic transits. Discharge volumes for the remaining 27 transits by vessels without prior history were estimated using data for vessels of similar type and size class, since ‘sister ships’ typically carry similar volumes of ballast water (Rup et al. 2010). Analysis of ballast water reports submitted by international and coastal domestic vessels indicated that 80 % of vessels loaded ballast at the last port-of-call, therefore we assigned the last port-of-call as the source of ballast water when ballast water history was incomplete. Further, we concluded that ballast was moved directly between domestic ports since domestic voyages are exempt from management regulations.

Ballast water exchange is documented as 90 % effective for saline source water and 99 % effective for freshwater sources, respectively (Ruiz and Smith 2005; Gray et al. 2007). Thus, the volume of ballast water discharged by vessels conducting ballast water exchange was corrected to account for the reduction in propagule pressure, using correction factors of 0.1 or 0.01 for vessels with ballast water from saline or freshwater source ports, respectively. For instance, a ship with reported discharge volume of 10,000 m^3 of ballast water, of which 6,000 m^3 originated from a saline source port and 4,000 m^3 from a freshwater source port, would be corrected using both correction factors resulting in 640 m^3 of ballast water being evaluated.

To characterize ballast water discharge patterns in the region, we summarized the geographic source location of ballast water by region, including the Arctic, Northwest Atlantic, Northeast Atlantic, West-central Atlantic, East-central Atlantic, Southeast Atlantic, and Mediterranean and Black Seas, as described by the Food and Agriculture Organization (FAO 2009) and as used in previous ballast water studies (see Simard and Hardy 2004; Claudi and Ravishankar 2006). Analysis

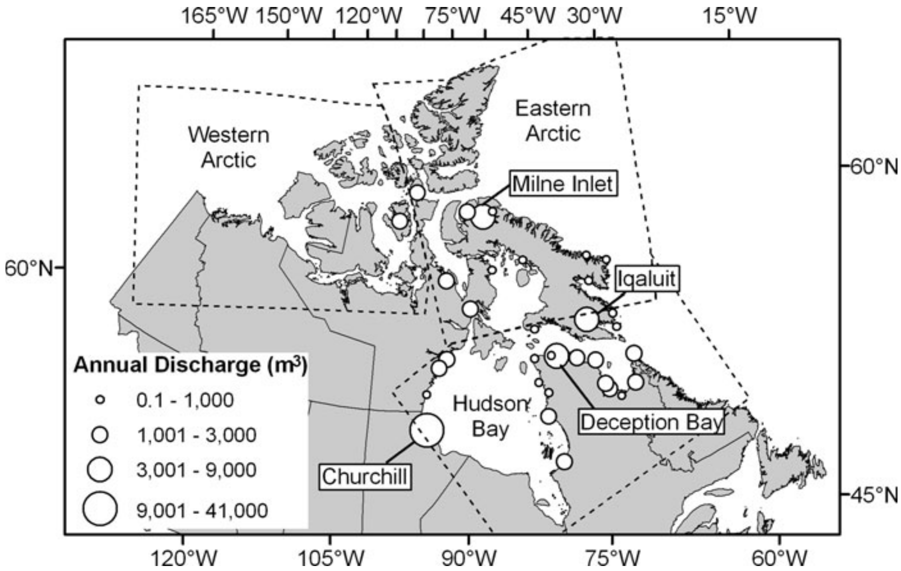

Fig. 1 Map illustrating the spatial distribution of corrected ballast water discharges in the Canadian Arctic by region: Hudson Bay, Eastern Arctic, and Western Arctic. *Dotted-line* polygons outline the boundaries of the Arctic regions, following Canadian Ice Services (2009). Top ports selected for full risk assessment are *labeled*

of Variance (ANOVA) was conducted to examine differences in annual discharge volume from different source regions (IMB SPSS Statistics 19, IMB Corp.). In addition, corrected ballast water discharge volumes were organized by month of discharge and operation region. In the absence of direct biological measures from ballast tanks, the corrected volume of ballast water discharged was used as a proxy for the propagule pressure of NIS potentially arriving at ports (Rup et al. 2010; Lo et al. 2011). A ranking system was used to convert volume of ballast water discharged into a relative probability of arrival, where the maximum mean annual corrected volume of ballast water discharged at any single Arctic port was divided into five equal categories (Table 1). We used a positive linear relationship between the two variables consistent with the linear multi-species models in previous ballast water studies (Ricciardi 2001, 2006; Drake and Lodge 2004; Reusser 2010). Owing to the large number of ports in the region, we prioritized the top three ports in each vessel category, based on the probability of arrival, for further assessment.

Estimating probability of survival and establishment

All ports directly connected as a ballast water source to each top Arctic port were noted, allowing identification of source-recipient port-pairs. A comparison of environmental similarity between port-pairs was conducted to estimate relative probability of survival and establishment for all possible species that may be released into the new environment by ballast water (Gollasch 2002; Clarke et al. 2004; Barry et al. 2008). We focused our analysis on temperature and salinity because they are fundamental factors affecting survival and reproduction of virtually all aquatic life (Anger 1991; Browne and Wanigasekera 2000). In addition, including variables that are related to invasion risk for only a subset of all potential NIS can dramatically influence the sensitivity of the environmental similarity measure (Barry et al. 2008). Following Keller et al. (2011), we selected four parameters to estimate environmental similarity between port-pairs, including annual mean water temperature, mean water temperature during the warmest month, mean water temperature during the coldest month, and annual mean salinity. Mean temperature provides a good indication of broad climatic zone, while maximum and minimum temperatures relate to upper and lower thermal limits of species (Angilletta 2009). A single salinity variable was used because it was the only salinity data available for most ports at a global scale (Keller et al. 2011). Data for the four parameters were obtained from Keller et al. (2011) for 6,651 ports worldwide. In addition, we interpolated environmental data in ArcGIS 10 (ESRI Inc.) for 56 Arctic ports not included in Keller et al. (2011) using data from the World Ocean Atlas (Antonov et al. 2006; Locarnini et al. 2006). All environmental variables were standardized using a z-transformation to remove scale differences (Clarke et al. 2004; Keller et al. 2011).

We calculated the environmental similarity between port-pairs using Euclidean distance in four-dimensional space (Clarke et al. 2004; Barry et al. 2008; Keller et al. 2011). Additionally, we conducted a linear regression and sensitivity analysis to determine the relative importance of each parameter in the environmental similarity calculations (see Keller et al. 2011). While salinity was found to have equal weighting as the three temperature variables combined in a study on the Great Lakes (Keller et al. 2011), environmental similarity between top Arctic ports and global ports is driven by mean temperature during the warmest month and mean temperature during the coldest month. While we could reduce the number of temperature variables to

Table 1 Ranking system for probabilities of arrival and survival and establishment and magnitude of consequence of NIS at Canadian Arctic ports

Mean annual corrected volume of ballast water discharged (m^3)	Environmental distance	Cumulative number of high impact NIS	Risk rating
27,734–34,667	0.00–1.40	701–875	Highest
20,801–27,733	1.41–2.80	526–700	Higher
13,867–20,800	2.81–4.20	351–525	Intermediate
6,934–13,866	4.21–5.60	176–350	Lower
0–6,933	4.61–7.00	0–175	Lowest

redistribute the influence of salinity in the environmental similarity calculations, we suggest that including all three temperature parameters is appropriate for this study because temperature range rather than salinity distinguishes top Arctic ports from other global ports. Similarly, a review by Chown et al. (2010) suggested that thermal extremes were more important than mean environmental temperature in determining species performance. Furthermore, we found that using different numbers and combinations of environmental variables in the environmental similarity calculation altered some risk ratings for individual port-pairs but did not change final invasion risk estimates.

Environmental distance values between each top port and all connected source ports were averaged to obtain a final rating for survival and establishment potential. A ranking system was used to convert the average environmental distance value for each port into a relative probability of survival and establishment, where the maximum value for any single source-recipient port-pair (of all possible global port-pairs, not just those that were connected in this dataset) was divided into five equal categories (Table 1). The choice of five equal categories reflects a positive linear correlation between the likelihood of NIS survival and establishment and the degree of environmental similarity between donor and recipient ports, an assumption that has been used in previous environmental matching studies (e.g., Hilliard et al. 1997; Hewitt and Hayes 2002; Clarke et al. 2004). We conducted the environmental similarity analysis on all possible global ports so that the ranking system would cover the full range of environmentally similar and dissimilar values (Clarke et al. 2004).

Calculating probability of introduction

Probabilities of arrival as well as survival and establishment were combined into a probability of introduction using Orr's (2003) minimum probability method. For example, a 'higher' probability of arrival combined with a 'lower' probability of survival and establishment would result in 'lower' probability of introduction. Because the outcome of each individual invasion stage is independent, but successful transition through all stages is a prerequisite for introduction, the probability of passing through all invasion stages would be equal to or lower than the probability of any individual stage (Orr 2003).

Estimating magnitude of potential consequence

We compiled a list of high impact ballast-mediated NIS for connected source ports using data from the Nature Conservancy's Marine Invasive Database (Molnar et al. 2008) because current, port-specific lists of native species and established NIS are not available globally. Molnar et al. (2008) quantifies NIS impact using a semi-quantitative ecological impact scoring system. The score was assigned globally for each species, reflecting the most damaging documented impact on the viability and integrity of native species and biodiversity (Molnar et al. 2008). Under this scoring system, all high impact NIS considered in the risk assessment have received a score of at least three in the four-point system, and disrupt multiple species, ecosystem function, and/or keystone or threatened species. The database includes 90 high impact ballast-mediated NIS in 232 ecoregions. We tabulated the number of high impact NIS recorded for the ecoregion of each connected source port assuming that each port may be a donor of all high impact NIS established within the ecoregion; therefore, multiple tally counts were given to a single NIS that could originate from multiple source ports within an ecoregion. For example, a top port connected to three different ecoregions via four source ports (two source ports being located within one ecoregion) with 10 high impact NIS recorded in each ecoregion would result in a cumulative total of 40 high impact NIS. A NIS originating from multiple source populations were tallied multiple times because the introduction of different genotypes of a single species can increase impact in the recipient environment through increased genetic variation and evolutionary potential (Sakai et al. 2001).

A ranking system was used to convert the cumulative number of high impact NIS connected to each top Arctic port into a relative magnitude of potential consequence, where the maximum value was divided into five equal categories (Table 1). We used a linear relationship between the two variables for two reasons. First, all high impact NIS considered have strong and roughly equal magnitude of consequences globally according to the ecological impact score system provided by Molnar et al. (2008). Therefore, a given increase in number of high impact NIS should lead to a proportional increase in the magnitude of potential consequence. Second, the linear impact

Table 2 Matrix used to combine probability of introduction and magnitude of consequence of introduction into final risk ratings, modified from Therriault and Herborg (2007); stippled = lower risk, grey = intermediated risk, black = higher risk

		P (Introduction)				
		Lowest	Lower	Intermediate	Higher	Highest
Consequence	Highest	▒	▒	■	■	■
	Higher	▒	▒	▒	■	■
	Intermediate	▨	▒	▒	▒	■
	Lower	▨	▨	▒	▒	▒
	Lowest	▨	▨	▨	▒	▒

model of Parker et al. (1999) describes impact as a function of abundance and effect per individual of a particular species; in this case, potential impact is a function of the number of potential high impact NIS and effect per species.

Calculating invasion risk

The probability of introduction and magnitude of potential consequences of ballast-mediated NIS were combined into a final relative invasion risk rating using a symmetrical mixed-rounding matrix that reduces the final ratings to three levels (modified from Therriault and Herborg 2007; Table 2).

Results

During the study period, 29 Arctic ports received an annual mean ballast water discharge of 275,714 (±6,644) m^3, or 92,625 (±11,251) m^3 after correcting for reduction in propagule pressure following ballast water exchange (Table 3). The number of discharge events decreased over time, though a similar volume was reported each year. Ninety-five percent of ballast water discharges took place between July and November, with peak discharge in August. The annual total corrected volume discharged differed significantly by source region (ANOVA, $p < 0.05$), with most water originating from Canadian ports in the Arctic (29,770 ± 9,852 m^2) and Northwest Atlantic (25,693 ± 11,344 m^3), followed by unknown sources (12,345 ± 5,318 m^3) and foreign ports in Northeast Atlantic (8,697 ± 2,166 m^3), Mediterranean and Black Seas (2,185 ± 678 m^3), West-central Atlantic (878 ± 608 m^3), East-central Atlantic (262 ± 262 m^3), and Southeast Atlantic (234 ± 234 m^3). Ballast water discharge patterns varied spatially, with ports in Hudson Bay receiving the greatest corrected volume of ballast water (76,145 ± 9,757 m^3), followed by those in the Eastern Arctic (16,308 ± 5,057 m^3) and Western Arctic (173 ± 173 m^3).

Twenty-seven (±1.7) international merchant vessels discharged an annual mean of 197,589 (±15,271) m^3 of ballast water, or 70,097 (±8,182) m^3 after correcting for reduction in propagule pressure following ballast water exchange. Churchill (Manitoba), Milne Inlet (Nunavut) and Deception Bay (Québec) received the greatest total corrected volume of ballast water discharged by international merchant vessels (Table 4). However, only Churchill had 'highest' probability for ballast-mediated NIS arrival via international merchant vessel discharges. Arrival probabilities for the remaining top ports ranged from 'lowest' to 'lower'. On the other hand, 12 (±2.0) coastal domestic merchant vessels discharged an annual mean of 78,125 (±13,802) m^3, or 22,528 (±3,947) m^3 corrected volume of ballast water. Churchill, Deception Bay and Iqaluit (Nunavut) received the greatest total corrected volume of ballast water discharged by coastal domestic merchant vessels (Table 4). The probability of arrival of ballast-mediated NIS via coastal domestic merchant vessel discharges was 'lowest' for all top Arctic ports.

Forty-eight foreign, two coastal domestic, and one Arctic source ports were connected to Churchill by international merchant vessels, with an 'intermediate' overall probability of survival and establishment; 29 source ports had 'higher' or 'highest' environmental similarity with Churchill (Appendix 1 in Supplementary Material). One coastal domestic source port was connected to Milne Inlet by international merchant vessels, with an 'intermediate' probability of survival

Table 3 Annual discharge statistics at Canadian Artic ports, by ballast water source

Years	Number of discharge events	Volume of ballast water discharge (m^3)								
		Grand Total	Corrected foreign exchanged		Corrected coastal domestic exchanged		Coastal domestic direct	Arctic direct	Unknown source	Corrected Total
			10 %	1 %	10 %	1 %				
2005	44	259,623	7,934	34	69	641	46,282	55,044	10,802	120,805
2006	41	291,652	15,402	0	1,025	513	0	50,190	25,927	93,057
2007	36	272,890	18,489	27	1,973	205	9,297	24,375	11,397	65,763
2008	35	278,690	11,846	0	0	820	38,548	39,663	0	90,877
Mean (±S.E.M.)	39 (2)	275,714 (6,644)	13,418 (2,277)	15 (9)	767 (465)	545 (130)	23,532 (11,178)	42,318 (6,788)	12,032 (5,321)	92,625 (11,251)

Correction factors (10 % for saline and 1 % for freshwater source ports, respectively) were applied to account for reduction in propagule supply due to ballast water exchange. 'Direct' refers to water that was not managed prior to discharge

and establishment (Appendix 1 in Supplementary Material). Similarly, one foreign, two coastal domestic, and one Arctic source ports were connected to Deception Bay by international merchant vessels, with a 'higher' overall probability of survival and establishment; four source ports had 'higher' or 'highest' environmental similarity with Deception Bay (Appendix 1 in Supplementary Material). One coastal domestic and five Arctic source ports were connected to Churchill by coastal domestic merchant vessels, with a 'highest' overall probability of survival and establishment; all of these source ports had 'highest' environmental similarity with Churchill (Appendix 2 in Supplementary Material). Five coastal domestic source ports were connected to Deception Bay by coastal domestic merchant vessels, with an 'intermediate' overall probability of survival and establishment; one source port had 'highest' environmental similarity with Deception Bay (Appendix 2 in Supplementary Material). Similarly, two Arctic source ports were connected to Iqaluit by coastal domestic vessels, with a 'highest' overall probability of survival and establishment; all source ports had 'highest' environmental similarity with Iqaluit (Appendix 2 in Supplementary Material).

Based on the probabilities of arrival as well as survival and establishment, all top ports have a 'lowest' to 'intermediate' probability of introduction of ballast-mediated NIS (Table 5). The cumulative number of high impact ballast-mediated NIS at each top port by vessel category ranged from one to 875, representing 78 distinct NIS (Table 5; Appendix 3 in Supplementary Material). Churchill was rated 'highest' for magnitude of potential consequence of NIS introduction via international merchant vessel discharges, while the remaining top ports rated 'lowest' for magnitude of potential consequence. The final relative invasion risk based on a combination of probability of introduction and magnitude of potential consequence indicated that Churchill has 'higher' risk for ballast-mediated invasions via international merchant ballast water discharges than any other recipient port studied (Table 5). The invasion risk for the remaining top ports was 'lower'.

Discussion

Using a relative risk assessment framework based on the estimated probability that potential NIS will

Table 4 Ballast water discharge statistics for international merchant and coastal domestic vessels at the top 5 Arctic ports

Top 5 ports	Number of discharge events	Mean (±S.E.M.) annual volume of ballast water discharge (m^3)		
		Grand total	Corrected total	P (arrival)
International merchant vessel ballast water discharges				
Churchill, MB*	17 (2)	157,675 (19,409)	34,667 (8,661)	Highest
Milne Inlet, NU*	0.3 (0.3)	6,959 (6,959)	6,959 (6,959)	Lower
Deception Bay, QC*	1.5 (0.3)	8,069 (4,020)	3,884 (2,073)	Lowest
Iqaluit, NU	1.3 (0.3)	3,679 (1,548)	3,679 (1,548)	Lowest
Aupaluk, QC	0.8 (0.3)	3,236 (1,105)	3,236 (1,105)	Lowest
Coastal domestic merchant vessel ballast water discharges				
Churchill, MB*	2 (1.4)	5,221 (3,319)	5,221 (3,319)	Lowest
Deception Bay, QC*	6 (1.2)	60,144 (11,852)	4,457 (2,102)	Lowest
Iqaluit, NU*	0.5 (0.3)	1,536 (896)	1,536 (896)	Lowest
Chesterfield Inlet/Igluligaarjuk, NU	0.3 (0.3)	1,468 (1,468)	1,468 (1,468)	Lowest
Nanisivik, QC	0.3 (0.3)	1,468 (1,468)	1,468 (1,468)	Lowest

* denotes the top three ports considered for full assessment in each vessel category

Table 5 Relative invasion risk for ballast-mediated introductions at top Arctic ports, by vessel category

	P (arrival)	P (survival and establishment)	P (introduction)	Cumulative number of high impact NIS	Magnitude of potential consequence	Invasion risk
International merchant vessel ballast water discharges						
Churchill, MB	Highest	Intermediate	Intermediate	875	Highest	Higher
Milne Inlet, NU	Lower	Intermediate	Lower	3	Lowest	Lower
Deception Bay, QC	Lowest	Higher	Lowest	47	Lowest	Lower
Coastal domestic merchant vessel ballast water discharges						
Churchill, MB	Lowest	Highest	Lowest	8	Lowest	Lower
Deception Bay, QC	Lowest	Intermediate	Lowest	12	Lowest	Lower
Iqaluit, NU	Lowest	Highest	Lowest	1	Lowest	Lower

successfully arrive, survive and establish, as well as the magnitude of potential consequence, Churchill appears to be at greatest invasion risk from discharge of ballast water by international merchant vessels despite requirements for ballast water exchange for incoming foreign transits. The estimated invasion risk is driven mainly by Churchill's high connectivity to a variety of foreign ports, and a high magnitude of potential impact in consequence. Churchill is a major Arctic seaport for grain export owing to its proximity to the Canadian prairies and its connection to the rail transit system, thus it attracts numerous international merchant vessels that discharge both domestic and foreign ballast water (McCalla 1994; Niimi 2007). All other ports assessed resulted in a lower invasion risk due to a low probability of NIS arrival and/or low magnitude of potential consequence.

Ballast water from coastal domestic sources in the Arctic and Northwest Atlantic appear to pose a relatively high risk of introducing new NIS or spreading established ones, representing 85 % of total corrected volume of ballast water discharged at Canadian Arctic ports. The majority of this volume was not exchanged because ballast water originating from domestic sources is presently exempt from ballast water management regulations. Moreover, domestic voyages are generally shorter and associated with higher density of viable organisms in ballast water discharges (Simkanin et al. 2009; Lawrence and Cordell 2010; DiBacco et al. 2011). On the other hand, ballast water from foreign sources must be exchanged or flushed on the open ocean, which dramatically reduces potential propagule pressure to Canadian ports. It is important to note that international merchant vessels did not always carry foreign ballast water; they also carried ballast water from domestic sources and appear to be the main vessel category delivering domestic ballast water and potentially NIS into the region (Appendix 4 in Supplementary Material).

The observed temporal and spatial patterns of ballast water discharge suggest that potential invasion risk is not uniform in the Canadian Arctic. Not surprisingly, ballast water discharges took place mainly during summer months, coinciding with high abundance of food and favorable environmental conditions for many species in the Arctic. The timing of propagule arrival may allow NIS to reproduce and form established populations or produce diapausing eggs before environmental conditions deteriorate, thus increasing the probability of successful colonization (Crawley 1989; Bailey et al. 2009). Additionally, discharges were concentrated in Hudson Bay, where climatic conditions are relatively mild and more similar to those of temperate regions, enhancing the probability of survival of released NIS. Therefore, ports in Hudson Bay may be at highest ballast-mediated invasion risk during summer months.

From a global perspective, the Canadian Arctic currently receives less vessel traffic and a smaller volume of ballast water discharge than most temperate regions. For example, the volume of ballast discharged in the region is 0.4 % of that in the Great Lakes and St. Lawrence River (Bailey et al. 2011) and 1 % of that on the west coast of the United States (Simkanin et al. 2009). The Canadian Arctic also has less vessel traffic than other Arctic regions, with approximately 10 % of the number of vessel arrivals to Alaska (McGee et al. 2006; Arctic Council 2009). It is important to note, however, that the short season and condensed spatial pattern of propagule arrival in the Canadian Arctic may negatively bias comparisons of annual averages. In addition, marine shipping in the Arctic is expected to grow in the near future coincident with sea ice retreat. Increased resource exploration, tourism, and research are expected to be major contributors to shipping growth in the Arctic (Arctic Council 2009). Current environmental conditions of some Arctic and sub-Arctic regions can be suitable for temperate species, thus successful establishment is possible given adequate propagule pressure (de Rivera et al. 2011). In fact, at least 10 NIS have been reported in Arctic and sub-Arctic waters, although the mechanism(s) of introduction and confirmation of long-term establishment success is generally not well documented (Hines and Ruiz 2000; Streftaris et al. 2005; Gollasch 2006; Molnar et al. 2008). The small number of NIS recorded in the Arctic may be an artifact of insufficient research effort (Niimi 2004; Ruiz and Hewitt 2009).

The Arctic remains a relatively pristine ecosystem with a relatively high number of endemic species (Arctic Council 2009). Precautionary preventive management efforts may protect Canadian and other Arctic ecosystems from biological invasions, especially at relatively high risk ports. Our results also suggest that vector management polices should include domestic ballast water carried by international merchant vessels. In addition, biological surveys can be directed at high-risk sites to gather information on the quantity and diversity of potential NIS associated with the vector and/or to fill data gaps. This framework can be used to monitor changes in invasion risk in the Canadian Arctic as the region experiences climate warming and increased shipping activity.

Several limitations of our relative risk assessment warrant discussion. First, our estimate of ballast water discharged by coastal domestic vessels into the region was largely based on the assumption that ballast water was discharged when cargo was loaded. This approach may over- or under-estimate actual volume discharged depending on the quantity of the cargo loaded in relation to the vessels' deadweight (David et al. 2012). In the absence of ballast information for this subset of vessels, our approach utilized best available data and was informed by government agencies and the shipping industry. Second, we used volume of ballast water discharged as a proxy measure for the biota actually released at ports. This relationship may not be robust in certain cases, with propagule pressure more strongly associated with water salinity, age of ballast water, and management practices (Verling et al. 2005; Lawrence and Cordell 2010). While our methods did account for ballast water exchange, we were unable to incorporate additional factors affecting propagule pressure. The use of ballast volume as a proxy for propagule pressure, while imperfect, is consistent with a number of previous studies (Drake and Lodge 2004; Herborg et al. 2007; Simkanin et al. 2009; Lo et al. 2011).

Third, the environmental similarity analysis may under- or over- estimate NIS survival and establishment risk for individual species because biological interactions, such as facilitation, competition and predation, which can have positive or negative impacts on NIS in the new environment, were not evaluated (Barry et al. 2008). While we recognize these limitations, our approach follows established assumptions and recommendations of previous environmental similarity analyses using the most comprehensive global port environmental data (e.g., Hewitt and Hayes 2002; Clarke et al. 2004; Barry et al. 2008; Keller et al. 2011). Finally, the list of high impact species used to estimate magnitude of potential consequence was available only for ecoregions rather than specific ports. It does not account for species that may cause high impacts in new recipient regions despite low or negligible impact in source regions, and it does not account for high impact species that are native to the source region. Additionally, the approach assumes that the effect per high impact NIS is independent of other species. Although NIS impacts are known to vary depending on the physical and biological characteristics of the invaded environment, we were not able to evaluate these factors due to limited port-specific NIS records. While not ideal, this data is peer-reviewed and is the most comprehensive global NIS data available.

All risk assessments have an inherent level of uncertainty since they are an estimate of a complex biological process and can never capture all variables involved (Orr 2003). In fact, risk assessments are most needed when knowledge regarding individual NIS or vectors is limited, or most uncertain. The uncertainty associated with our vector-based relative risk assessment is mainly related to the quality of data (degree of error) available and the representativeness of the data in terms of the invasion process (degree of mismatch). The degree of error in our relative assessment is generally low because all data used were obtained from extensive systematic information or peer-reviewed data. The degree of mismatch is low to moderate because the relationship between invasion success and the proxy measures used to estimate probabilities of arrival, survival and establishment, and consequence were based on substantial scientific information and peer-reviewed literatures. The National Research Council (2011) provided an extensive theoretical treatment of the risk-release relationship, surmising that the combined curves of multiple populations would be expected to be non-linear but might be better characterized as linear due to other important sources of variation that affect invasion probability. Thus, we chose a linear model for our relative ranking system, which is consistent with previous ballast water studies (e.g., Ricciardi 2001, 2006; Drake and Lodge 2004; Reusser 2010). We acknowledge that additional research to improve the degree of mismatch would benefit future vector-based risk assessments.

To our knowledge, this is the most comprehensive vector-based relative risk assessment for assessing potential invasions where the identity of NIS associated with the vector is unknown. By evaluating all stages of the invasion process and the magnitude of potential consequence, we estimated the relative invasion risk at major ports and identified risky transit pathways for the Canadian Arctic. The framework presented here could be applied to other mechanisms of biological invasion where the vast number of potential NIS within a vector prohibits species-specific assessment. The information needed will vary according to vector but should include a measure of vector strength such as the number of arrivals, identification of source and release sites of potential NIS (i.e., the pathway), environmental conditions at those sites, as well as a means to measure potential consequence. By following these steps and adopting a risk ranking system, one can estimate the relative probability of introduction and potential magnitude of consequence for NIS within a vector at a variety of locations or across different geographic pathways.

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