SCIENCE ADVICE FROM THE RISK ASSESSMENT FOR SHIP-MEDIATED INTRODUCTIONS OF AQUATIC NONINDIGENOUS SPECIES TO THE CANADIAN ARCTIC

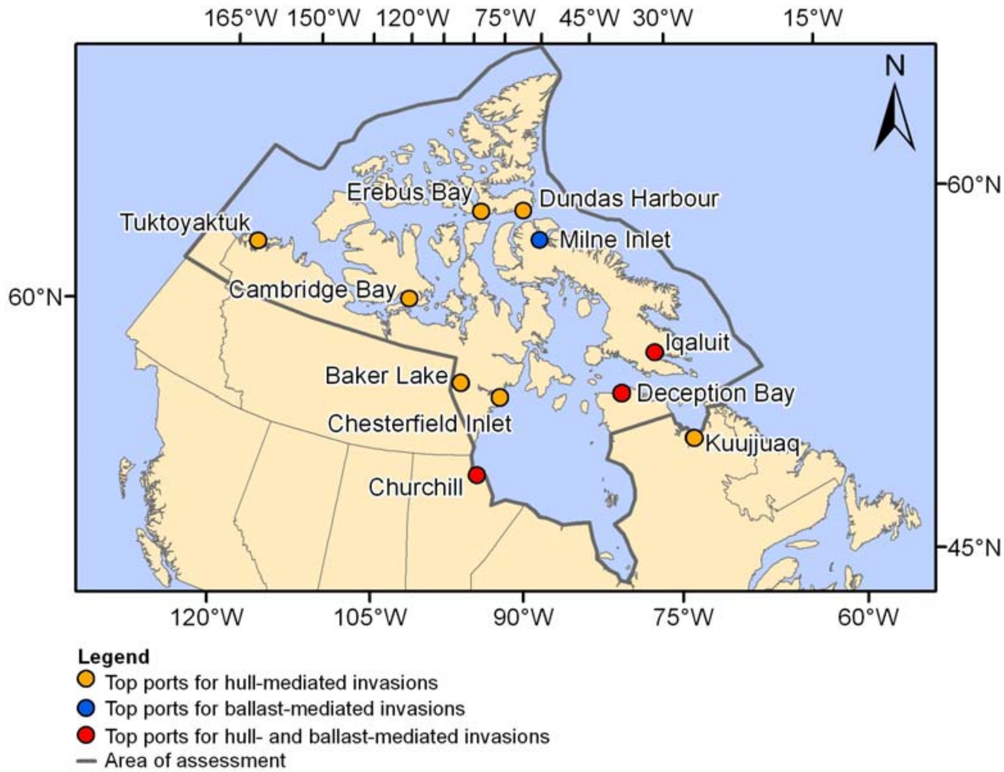

Figure 1. Locations of top Arctic ports based on the number of vessel arrivals or volume of ballast water discharged.

Context :

Transport Canada (Marine Safety) is tasked with managing a regulatory program that sets shipping procedures in order to reduce the risk of ship-mediated transfer of invasive species. Current ballast water regulations are being revised and Transport Canada has submitted a formal request to Fisheries and Oceans Canada (DFO) for science advice on the level of risk posed by the commercial shipping vector to Canadian waters. DFO's Centre of Expertise for Aquatic Risk Assessment (CEARA) has established guidelines for assessing the biological risk of aquatic invasive species in Canada.

The objective of the current advisory process is to assess the level of risk posed by ships transiting to, or from, Arctic ports for the introduction of aquatic invasive species to Canadian waters and the level of risk posed by domestic shipping activities.

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat national meeting held March 1-2, 2011 in Burlington ON to assess the risk of ship-mediated introduction of nonindigenous species in the Canadian Arctic. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

SUMMARY

- Canadian Arctic ports are utilized by international and domestic ships, resulting in potential for species transfers between connected ports *via* hull fouling and ballast water discharge vectors.
- Introduction of non-indigenous species (NIS) can potentially cause great ecological, social and economic harm to an area.
- This study ranks relative risk posed by ship-mediated introduction of NIS to Arctic ports based on 2005-2008 shipping data and recent environmental data.
- In order of importance, Churchill, MB; Iqaluit, NU and Erebus Bay/Beechey Island, NU are identified as Arctic ports with the highest relative risk of environmental consequences due to introduction of NIS *via* hull fouling.
- Churchill, MB is the Arctic port with the highest relative risk of environmental consequences due to introduction of NIS *via* ballast water discharge.
- Biological sampling of ship vectors should be conducted to further quantify/calibrate invasion risk with consideration of species-specific and site-specific characteristics.
- Future research and/or monitoring activities at Arctic ports should be prioritized at locations identified as higher risk by this assessment.
- As a number of ports are now being planned or developed in the Arctic, shipping patterns may change significantly. If shipping traffic or global climate conditions change, a re-assessment may be required.

INTRODUCTION

It is now common to hear of negative impacts to natural ecosystems caused by nonindigenous species (NIS). NIS are the second greatest cause of extinction globally and the greatest threat to biodiversity in freshwater ecosystems. Long-term economic consequences of NIS have cost industry and society (directly and indirectly) an estimated $13.3 to $34.5 billion/year in Canada.

Founding individuals, called propagules, must arrive at a new location and must be able to survive the environmental conditions of the new area. They must survive long enough and in great enough numbers to reproduce and become established in an area. They may then spread from the localized area of establishment by various means to become widespread in a region. Shipping has been identified as a major vector in the transport of aquatic NIS around the world.

Ballast water is pumped into ballast tanks of a ship to control trim and stability, and to prevent hull stress. Diverse communities of plankton present in the water are inadvertently pumped into ballast tanks as the water is loaded. At port, sediments and their associated organisms can be re-suspended by shipping activities and also taken in with ballast water. Ballast water may then be transported to a new port and discharged, providing opportunity for release of NIS.

Vessel type, size and trade patterns influence the invasion risk associated with a particular vessel. Merchant vessels such as bulk carriers and tankers are higher risk for ballast-mediated transport of NIS, while ships that do not regularly discharge ballast such as tugboats and passenger ships are less important for introductions *via* ballast. Trans-oceanic vessels have been considered the primary pathway for NIS introductions since they connect distant ports, but domestic or coastal vessels contribute to secondary spread of established NIS within a region.

Hull fouling is another means by which shipping activities can transport NIS around the world. Sessile organisms such as algae, hydroids, bryozoans, barnacles and other bivalves can form dense colonies on external underwater surfaces that may provide structural habitat and protection for crustaceans and other mobile taxa. Fouling taxa can become detached or release reproductive propagules anywhere along the shipping route.

As with ballast water, operational characteristics of the vessel and its trading patterns influence invasion risk. Invasion risk increases with increased mooring time and time elapsed since last application of antifouling coating system. Risk decreases as vessel speed increases, producing shear forces that can remove or kill organisms attached to the hull. In addition, trade route can influence risk: ships which pass through highly variable environments, such as moving from low salinity coastal waters to euhaline ocean waters, pose lower risk than ships operating within a more continuous environment.

Ballast Water Management Regulations

Ballast water exchange (BWE) is a process by which a ship exchanges ballast water loaded at port with water from the open ocean. It is hypothesized that any open-ocean taxa released with exchanged ballast water will not thrive in coastal and freshwater port environments and will be low-risk for invasion. In 2000, Canada established ballast water management regulations which require all vessels at least 50 m in length and having at least eight m^3 ballast capacity, that enter and operate in Canadian waters, to conduct BWE at sea. There are the following exceptions:

(i) Ships that operate exclusively in Canadian waters;

(ii) Vessels used in government non-commercial service;

(iii) Ships that carry only permanent ballast in sealed tanks.

In order to maximize BWE efficiency, ballast tanks that are exchanged by the empty-refill method must replace at least 95% of their ballast water while vessels conducting flow-through exchange must pump a minimum of three tank-volumes through each ballast tank. The exchanged ballast water must have a final salinity of ≥ 30 ‰. BWE must be conducted at least 200 nautical miles from land at ≥ 2000 m depth. If a vessel does not pass through an appropriate exchange area, Canada will accept exchange in an alternate exchange zone (≥ 50 miles offshore and ≥ 500 m depth).

In 2006, additional regulations were implemented to reduce the risk of invasion posed by organisms in residual water or sediment in ballast tanks considered empty by industry standards. These tanks must now be flushed with open-ocean water to achieve a final salinity of ≥ 30 ‰. Ballast sediment must now be monitored and should be disposed of at a reception facility.

Studies indicate that BWE physically removes 80-100% of coastal planktonic organisms, and further reduces the risk of freshwater or low salinity NIS by causing salinity shock. However, in accordance with proposed international standards, BWE is to be phased out and replaced by shipboard ballast water treatment systems, such as filtration, biocides and/or chlorination, by 2016.

Specific Issues of Concern

The Canadian Arctic is home to over 100,000 Canadians, abundant animal and plant life, and large deposits of important minerals. In addition, there are many ecologically senstive areas in the region which may be vulnerable to impacts from shipping. The Arctic has previously been thought to be at low risk for aquatic invasions because the harsh environmental conditions are expected to provide partial protection against NIS. A relatively low level of shipping activity, as compared to more temperate ports, is also thought to reduce risk.

Taxa fouling ship hulls may be scraped off by sea ice, potentially decreasing invasion risk if individuals are killed by the process, but risk may increase if the process releases viable propagules at a variety of locations. Only 10 NIS are known to occur in Arctic waters globally, although this number is likely biased by limited research effort and taxonomic knowledge. A lack of baseline data leads to problems determining whether a newly reported species is native or NIS. Climate change may alter temperature regimes, sea level, and ocean currents, leading to changes in species' rates of natural dispersal and survival. Changes in human activities (e.g., new shipping routes) may create new human-mediated routes of invasion to the Arctic.

RISK ASSESSMENT

Shipping activities at Arctic ports during the 2005-2008 shipping seasons were considered in the assessment. Ship-mediated risk was assessed for species transported by ballast water and by hull fouling. Information on vessel type, ballast water status and discharge volume at specific Arctic ports was combined with data on environmental conditions at Canadian and international ports directly connected to top Arctic ports to estimate relative probabilities of introduction. Data on the number of high impact NIS at connected ports was used to determine the potential consequences of introduction. The probability of NIS introduction and magnitude of consequences were subsequently combined to determine the final relative invasion risk at top Arctic ports.

Information Sources and Ship Categorization

The Canadian Coast Guard's Information System on Marine Navigation (INNAV) and Transport Canada's Ballast Water Database contain records of arrival and departure events, and cargo and ballast operations in port, for all commercial vessels entering the Canadian Maritime Communications and Traffic Services Zone. Shipping data were organized by port, month of arrival, vessel type (merchant, Coast Guard, fishing, passenger, tug/barge, research and special purpose) and operational region (international, coastal domestic and Arctic) (Table 1).

Table 1. Vessel classification system, based on operational region and ship type, with corresponding definitions and examples (from Chan et al. 2011).

	Definition/Example
Operational region	
Arctic	Vessels that operated exclusively within the Canadian Arctic region during the study period and are not required to conduct ballast exchange/flushing
Coastal domestic	Vessels that operated exclusively within the Canadian Exclusive Economic Zone (EEZ) during the study period and are not required to conduct ballast exchange/flushing
International	Vessels that operated outside of the Canadian EEZ for at least part of the study period and are required to conduct ballast exchange/flushing prior to entering the Canadian EEZ; some vessels will move domestic ballast water (not required to exchange/flush) on subsequent voyages within the EEZ
Ship type	
Merchant	Bulk carriers, tankers, general cargo, and roll on/roll off vessels
Coast Guard	Coast guard tenders and icebreakers
Fishing	Fishing vessels and trawlers
Passenger	Cruise ships and yachts
Research	Research vessels
Special Purpose	Cable vessels and heavy-lift ship
Tug/Barge	Supply tugs, harbour tugs, ocean tugs, and barges

The Nature Conservancy's Marine Invasive Database (Molnar et al. 2008) contains a list of invasive species and classifies them by geographic region, potential pathway of spread (i.e., hull fouling or ballast water) and expected impact on an invaded ecosystem. High impact NIS were defined as those that disrupt multiple species, ecosystem function and/or keystone or threatened species.

Determination of Hull Fouling-Mediated Invasion Risk

Risk of invasion *via* hull fouling was estimated for merchant and non-merchant vessels using the following steps.

1. PROBABILITY OF ARRIVAL: The number of vessel arrivals was used as a coarse proxy for number of propagules introduced to a port by hull fouling, recognizing that factors such as voyage history and anti-fouling management practices can have strong influence on arrival probability but are much more difficult to assess; this estimate therefore has moderate uncertainty. Due to the large number of ports in the region and limited time and resources available to complete the risk assessment, the top three ports in each vessel category were prioritized for further assessment.
2. PROBABILITY OF SURVIVAL: Given that global research indicates that hull fouling is an important vector for coastal marine ports but not freshwater ports, the probability of survival of propagules at potential recipient Arctic ports was estimated to be lowest if the recipient port was freshwater and highest if the port was brackish or saline. This estimate carries a moderate level of uncertainty since salinity can vary both spatially and temporally with a single port and because other physical variables such as pH, dissolved oxygen or depth, and biological factors such as species interactions influence survival but could not be addressed considering the wide array of requirements by different species in a pathway risk assessment.
3. PROBABILITY OF INTRODUCTION: The probabilities of arrival and survival were combined to determine the probability of introduction. Since both arrival and survival

must occur for NIS establishment, the lowest probability was retained as the probability of introduction. The highest level of uncertainty was retained for this estimate.

4. MAGNITUDE OF POTENTIAL CONSEQUENCES: A list of high impact fouling NIS established in all connected source ports was used to estimate the magnitude of potential consequences, assuming that a greater number of high impact NIS with potential for introduction would result in a greater overall impact on that port. Since data for high impact species was available for ecoregions rather than specific ports and it is difficult to predict effects of NIS introduced to new locations, the level of uncertainty associated with this estimate is moderate.
5. RELATIVE RISK: The probability of introduction was combined with the magnitude of potential consequences using a risk matrix (Table 2) to determine the relative level of risk posed to individual ports by the hull fouling vector. The highest level of uncertainty associated with the two input components was retained.

Table 2 The mixed rounding symmetrical approach used to combine probability of introduction and magnitude of potential impact ratings to determine final invasion risk at each Arctic top port for each ship category. Five levels of probability and impact ratings ranging from lowest (blue) to highest (red) are combined into a final invasion risk ranging from lower (green) to higher (orange).

Magnitude of potential impact \ Probability of introduction	Lowest	Lower	Intermediate	Higher	Highest
Highest	Yellow	Yellow	Orange	Orange	Orange
Higher	Yellow	Yellow	Yellow	Orange	Orange
Intermediate	Green	Yellow	Yellow	Yellow	Orange
Lower	Green	Green	Yellow	Yellow	Yellow
Lowest	Green	Green	Green	Yellow	Yellow

6. SECONDARY SPREAD: An additional measure, called ship-mediated spread potential, was determined to rank a port's potential to facilitate stepping-stone, or inter-regional, invasions *via* hull fouling. Assuming that each domestic vessel that arrived at an Arctic port would subsequently depart to a different Canadian port, the number of domestic vessel arrivals was used to estimate potential for secondary spread. Since this estimate considers only one of many potential vectors of secondary spread and measures risk nationally rather than for a specific port, it was not included in the calculation of relative risk.

Determination of Ballast-Mediated Invasion Risk

Relative risk to Arctic ports via ballast water discharged by merchant vessels was assessed using the following steps.

1. PROBABILITY OF ARRIVAL: The volume of ballast water discharged was used to estimate the number of propagules introduced to a port by ballast water, recognizing that volume of ballast water discharged is not a direct measurement of the probability of arrival. Only merchant vessels were considered as other vessel types carry very little or no ballast water. Correction factors were applied to account for the decreased number of propagules in exchanged ballast water. The last port of call was assumed to be the ballast source when records were not available. This estimate was considered to have

low uncertainty. Due to the large number of ports in the region and limited time and resources available to complete the risk assessment, the top three ports in each vessel category were prioritized for further assessment.

2. PROBABILITY OF SURVIVAL: The fundamental physical factors affecting survival and reproduction of aquatic organisms are temperature and salinity. These factors were used to calculate an environmental similarity (ES) ranking for each source-recipient port- pair. The average ES of all ports directly connected to each top Arctic port was used as a measure of probability of survival at each port. This estimate had a moderate degree of uncertainty because other physical variables, such as pH, dissolved oxygen or depth, and biological factors, such as species interactions, influence survival but could not be addressed considering the wide array of requirements by different species in a pathway risk assessment.
3. PROBABILITY OF INTRODUCTION: The probabilities of arrival and survival were combined to determine the probability of introduction. Since both arrival and survival must occur for NIS establishment, the lowest probability was retained as the probability of introduction. The highest level of uncertainty was retained for this estimate.
4. MAGNITUDE OF POTENTIAL CONSEQUENCES: A list of high impact ballast-mediated NIS established in all connected source ports was used to estimate the magnitude of potential consequences, assuming that a greater number of high impact NIS with potential for introduction would result in a greater overall impact on that port. Since data for high impact species was available for ecoregions rather than specific ports and it is difficult to predict effects of NIS introduced to new locations, the level of uncertainty associated with this estimate is moderate.
5. RELATIVE RISK: The probability of introduction was combined with the magnitude of potential consequences using a risk matrix (Table 2) to determine the relative level of risk posed to individual ports by NIS transported in ballast water. The highest level of uncertainty associated with the two input components was retained.
6. SECONDARY SPREAD: An additional measure, called ship-mediated spread potential, was determined to rank a port's potential to facilitate stepping-stone, or inter-regional, invasions *via* ballast water. Assuming that each domestic vessel that loaded ballast water at an Arctic port would subsequently discharge that ballast at a different Canadian port, the number of ballast uptakes was used to estimate potential for secondary spread. Since this estimate considers only one of many potential vectors of spread, and applies to the region rather than a port, it was not included in assessment of relative risk to individual ports.

Results

The results of the risk assessment indicating relative invasion risk posed to, and the potential spread from, top Arctic ports by hull fouling are presented in tables 3 and 4. The results of the ballast water mediated risk assessment for the top Arctic ports are presented in tables 5 and 6.

Table 3. Relative invasion risk to top Arctic ports by hull fouling NIS, by vessel category, with level of uncertainty indicated in brackets below each column heading.

	P(Introduction) (moderate)	**Magnitude of consequence** (moderate)	**Invasion risk** (moderate)
Top ports for international merchant arrivals			
Churchill, MB	Highest	Highest	Higher
Iqaluit, NU	Higher	Lowest	Intermediate
Deception Bay, QC	Intermediate	Lowest	Lower
Top ports for coastal domestic merchant arrivals			
Iqaluit, NU	Highest	Lowest	Intermediate
Deception Bay, QC	Intermediate	Lowest	Lower
Kuujjuaq (Fort Chimo), QC	Lower	Lowest	Lower
Top ports for international non-merchant arrivals			
Erebus Bay/Beechey Island, NU	Higher	Lowest	Intermediate
Iqaluit, NU	Intermediate	Lowest	Lower
Dundas Harbour, NU	Intermediate	Lowest	Lower
Top ports for coastal domestic non-merchant arrivals			
Baker Lake/Qaminituak, NU	Lowest	Lowest	Lower
Churchill, MB	Intermediate	Lowest	Lower
Chesterfield Inlet/Iguligaarjuk, NU	Intermediate	Lowest	Lower
Top ports for Arctic non-merchant arrivals			
Cambridge Bay/Ikaluktutiak, NU	Intermediate	Lowest	Lower
Tuktoyaktuk, NT	Intermediate	Lowest	Lower
Baker Lake/Qaminituak, NU	Lowest	Lowest	Lower

Table 4. Departure statistics for coastal domestic and Arctic vessels from top Arctic ports as a measure of potential for hull-mediated secondary spread.

	Mean (± S.E.M.) annual number of departures	**P(Spread)**
Top ports for international merchant vessels		
Churchill, MB	15.00 (± 3.08)	Higher
Iqaluit, NU	21.50 (± 2.06)	Highest
Deception Bay, QC	11.25 (± 1.70)	Intermediate
Top ports for coastal domestic merchant vessels		
Iqaluit, NU	21.50 (± 2.06)	Highest
Deception Bay, QC	11.25 (± 1.70)	Intermediate
Kuujjuaq (Fort Chimo), QC	6.25 (± 1.18)	Lower
Top ports for international non-merchant vessels		
Erebus Bay/Beechey Island, NU	0.00 (± 0.00)	Lowest
Iqaluit, NU	21.50 (± 2.06)	Highest
Dundas Harbour, NU	0.25 (± 0.25)	Lowest
Top ports for coastal domestic non-merchant vessels		
Baker Lake/Qaminituak, NU	18.75 (± 7.18)	Highest
Churchill, MB	15.00 (± 3.08)	Higher
Chesterfield Inlet/Iguligaarjuk, NU	15.00 (± 5.73)	Higher
Top ports for Arctic non-merchant vessels		
Cambridge Bay/Ikaluktutiak, NU	10.25 (± 2.06)	Intermediate
Tuktoyaktuk, NT	9.00 (± 1.00)	Intermediate
[1]Baker Lake/Qaminituak, NU	18.75 (± 7.18)	Highest

[1]Note that Baker Lake is freshwater and hull fouling NIS are likely to be marine. Any freshwater NIS that may foul ship hulls at Baker Lake are likely to die in transit through marine waters to the next port.

Table 5. Relative invasion risk to top Arctic ports by ballast-mediated NIS, by vessel category, with level of uncertainty indicated in brackets below each column heading.

	P(Introduction) (moderate)	**Magnitude of consequence** (moderate)	**Invasion risk** (moderate)
Top ports for international merchant ballast water discharges			
Churchill, Manitoba	Intermediate	Highest	Higher
Milne Inlet, Nunavut	Lower	Lowest	Lower
Deception Bay, Québec	Lowest	Lowest	Lower
Top ports for coastal domestic merchant ballast water discharges			
Churchill, Manitoba	Lowest	Lowest	Lower
Deception Bay, Québec	Lowest	Lowest	Lower
Iqaluit, Nunavut	Lowest	Lowest	Lower

Table 6. Ballast water uptake statistics for coastal domestic merchant vessels at top Arctic ports as a measure of potential for ballast-mediated secondary spread.

	Mean (± S.E.M.) annual number of ballast water uptake events	**P(Spread)**
Top ports for international merchant vessels		
Churchill, MB	1.75 (± 0.75)	Lowest
Milne Inlet, NU	0.50 (± 0.50)	Lowest
Deception Bay, QC	3.50 (± 2.18)	Lower
Top ports for coastal domestic merchant vessels		
Churchill, MB	1.75 (± 0.75)	Lowest
Deception Bay, QC	3.50 (± 2.18)	Lower
Iqaluit, NU	14.50 (± 1.66)	Highest

Sources of Uncertainty

Pathway risk assessments must consider a large variety of species transported over time, many of which are unknown. As a result, there is a reliance on more generalized methods, which have an inherent level of uncertainty.

The number of ship arrivals and volume of ballast water discharged were used as proxy measures of probability of arrival. While these measures are commonly used in the literature, they are not direct measures of propagule supply, and their use adds a level of uncertainty to the assessment.

Port-specific attributes, including environmental conditions (temperature and salinity) and species composition, vary both temporally and spatially and are not well-documented globally, providing another key source of uncertainty.

Five equal categories were used in this risk assessment to rank probabilities and risk levels, based on the assumption of a linear relationship, which is consistent with invasion theory but not quantified.

CONCLUSIONS

Canadian Arctic ports are connected to international and coastal domestic ports, resulting in potential for species transfers via hull fouling and/or ballast water discharge.

Although most ship arrivals and ballast water discharge originated from foreign ports, coastal domestic ports may contribute the greatest propagule supply to the Arctic due to shorter vessel transits, exemption from ballast water exchange, and higher environmental similarity between source and recipient ports.

In order of importance, Churchill, MB; Iqaluit, NU and Erebus Bay/Beechey Island, NU are identified as Arctic ports with the highest risk of environmental consequences due to introduction of NIS *via* hull fouling while Churchill, MB is at highest risk *via* ballast water discharge.

Port Alfred (Québec) is a potentially important source of ballast-mediated NIS for Churchill due to relatively high propagule supply and environmental similarity.

The authors recommend biological sampling of ship vectors and recipient port habitats to quantify/calibrate invasion risk with consideration of species-specific and site-specific characteristics. Future research should be prioritized at the ports identified as higher risk by this assessment.

OTHER CONSIDERATIONS

This pathway risk assessment was based on 2005-2008 shipping data and recent environmental data, representing only a snapshot in time. If shipping traffic patterns in the Arctic or global climate conditions change significantly, a re-assessment may be required.

The ranking system used in this risk assessment is relative, allowing prioritization of Arctic ports. Ports identified as higher risk in this study may not be high risk in a national scale considering, for example, the relatively low international shipping traffic in the region. Furthermore, delineating an acceptable level of risk is a decision to be made by risk managers and/or stakeholders.

SOURCES OF INFORMATION

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, national advisory meeting of March 1-2, 2011 on the Risk Assessment for ship-mediated introductions of aquatic nonindigenous species to the Great Lakes and the Canadian Arctic. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

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