



# Screening for High-Risk Marine Invaders in the Hudson Bay Region, Canadian Arctic

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The Canadian Arctic is receiving increased ship traffic, largely related to non-renewable resource exploitation and facilitated by climate change. This traffic, much of which arrives in ballast, increases opportunities for the spread of aquatic invasive species (AIS). One of the regions at greatest risk is the Hudson Bay Complex. A horizon scanning exercise was conducted using the semi-quantitative Canadian Marine Invasive Screening Tool (CMIST) to identify AIS of potential concern to the region. This screening-level risk assessment tool, uses documented information to answer questions related to the likelihood and impact of invasion. Species were analyzed by ecological categories (zoobenthos, zooplankton, phytobenthos) and taxonomic groups, with 14 species (out of 31) identified as being of highest relative risk. Crabs, mollusks, macrozooplankton and macroalgae were the taxonomic groups with the highest overall risk scores, through a combination of higher likelihood of invasion and impact scores relative to other taxa. Species that may pose the highest AIS risk are currently mainly distributed on the east and west coasts of the North Atlantic Ocean. Their distributions coincide with source ports and shipping pathways that are well connected to the Hudson Bay Complex. This first horizon scan to identify potential high-risk AIS for the Canadian Arctic incorporated two novel approaches into the CMIST analysis: i) use of the tool to assess two new ecological categories (phytobenthos and zooplankton), and ii) use of averaged CMIST results to interpret general risk patterns of ecological categories. This study is also the first to use CMIST scores to highlight common source regions and connected ports for the highest risk species. In a scenario of climate change and increasing ship traffic, this information can be used to support management actions such as the creation of watch lists to inform adaptive management for preventing AIS establishment, and mitigating associated environmental and economic impacts.

**Keywords:** aquatic invasive species, horizon scanning, risk assessment, Canadian Marine Invasive Species Tool, watch list

## INTRODUCTION

To stop biodiversity loss, Aichi Biodiversity Target 9 from The Strategic Plan for Biodiversity 2011–2020 states that invasive species and their pathways need to be identified and managed to take effective actions to prevent introductions and establishments (CBD Secretariat, 2010). Many recent extinctions and losses of biodiversity have been driven by invasive species (Bellard et al., 2016;

Blackburn et al., 2019). Economic impacts due to invasive species have been estimated at up to 12% of the gross domestic product of affected countries (Marbuah et al., 2014). Deleterious effects can occur at ecological levels ranging from populations and communities to habitats, ecosystem functioning, and ecosystem services (e.g., Gallardo et al., 2016a; Anton et al., 2019). A key first step to attain Aichi Biodiversity Target 9, is to identify potential invasive species and assess their likelihood of introduction and impact.

Aquatic invasions are an emerging issue in Arctic ecosystems (Ricciardi et al., 2017), where global change, growing shipping activity, and natural resources exploitation may increase invasion risk (Niimi, 2004; Smith and Stephenson, 2013; Miller and Ruiz, 2014; Melia et al., 2016; Essl et al., 2020). The Canadian Arctic is a vast region where remoteness and harsh climate limit opportunities for year-round monitoring and early detection of aquatic invasive species (AIS). In this area, the identification of high-risk species, pathways, and geographic locations is particularly important for informing targeted preventative and surveillance measures to limit introduction and spread of AIS.

The Canadian Arctic is warming about three times faster than the global rate (Flato et al., 2019), creating conditions favorable for the survival and establishment of new species in the region. The Hudson Bay Complex is an area of the Canadian Arctic where reductions in sea ice cover (duration and concentration) are among the greatest observed in Arctic regions (Stammerjohn et al., 2012; Mudryk et al., 2018). Indeed, sea ice cover there has been declining at a rate of 10.8% per decade since the mid-1990s (Derksen et al., 2018), and ice-free time is projected to double (from 2 to 4 months) by mid-century (Tivy et al., 2011; Mudryk et al., 2018).

Rates of species introduction and AIS establishment are low in the Canadian Arctic relative to temperate regions (Casas-Monroy et al., 2014; Chan et al., 2019). However, new introductions and non-native species are being reported (MacDonald et al., 2010; Mathieson et al., 2010; Goldsmith et al., 2014; Golder (Golder Associates Ltd.), 2018; Dhifallah, 2019; Dispas, 2019) or detected in the environment using genetic tools (Brown et al., 2016; Chain et al., 2016; Grey et al., 2018; Lacoursière-Roussel et al., 2018; Leduc et al., 2019). Ports of call for vessels visiting the Arctic often host species with considerable potential for establishing there. Distribution modeling studies predict that suitable habitat exists in the Canadian Arctic for some potentially high-risk invasive species under current climatic conditions and that Arctic habitats will become increasingly suitable under future change scenarios (Ware et al., 2016; Goldsmith et al., 2018, 2020).

Domestic and international shipping are likely the primary anthropogenic vectors for introducing marine aquatic invasive species to the Canadian Arctic (Chan et al., 2012; Goldsmith et al., 2019). The former plays a fundamental role in supplying local communities and export of mineral resources, and the latter in the export of renewable (e.g., grain) and non-renewable (e.g., ore) resources (Chan et al., 2012; Gavrilchuk and Lesage, 2014; Goldsmith et al., 2019). The risk of introduction is great as ships from both sources transport non-indigenous species in their ballast water and attached to their hulls (Chan et al., 2015; Laget, 2017; Tremblay, 2017; Dhifallah, 2019; Dispas, 2019). Domestic

ships, in particular, pose a moderate to high ecological risk in the region (Goldsmith et al., 2019). They often arrive loaded, which reduces the incoming volume of ballast water, but those that do arrive in ballast are exempt from management and undertake shorter transits, which may facilitate the successful transport of viable AIS. Although international vessels typically arrive in ballast, they are required to exchange and/or treat their ballast water (IMO (International Maritime Organization), 2004; Canada Gazette, 2019). However, the efficacy and reliability of various treatment methods for reducing the number of live organisms in vessels can be quite low (DFO (Department of Fisheries and Oceans), 2019) and remains uncertain, particularly under colder conditions, such as those encountered in Arctic waters. Thus, the ecological risk posed by international shipping in Arctic waters may be high. In addition, the trend toward a longer open water season is expected to increase the exposure of local communities to shipping traffic (Andrews et al., 2018). Moreover, significant increases in marine shipping are expected in response to population growth, declining sea ice, and resource extraction (Lasserre, 2018). For example, Baffinland Iron Mines Corporation is currently exporting close to 6 Mt of iron ore annually from its Mary River mine at the northern end of Baffin Island via Milne Inlet, Eclipse Sound and Baffin Bay to markets in Europe and Asia (Baffinland (Baffinland Iron Mines Corporation), 2020a), with a proposed increase to 12 Mt currently under review (Baffinland (Baffinland Iron Mines Corporation), 2020b). A proposal to ship an additional 18 Mt of iron ore annually from the mine via Steensby Inlet, Foxe Basin, and Hudson Strait to markets in Europe and elsewhere has been approved and may be operational by 2028 (Baffinland (Baffinland Iron Mines Corporation), 2020b).

Prevention is key to invasive species management (Lockwood et al., 2007). Once an invasive species has established a reproducing population, it is typically very difficult or impossible to eradicate (Locke and Hanson, 2009). Identifying species that are most likely to harm a particular risk assessment (RA) area is a key step toward preventing introductions and supporting a rapid response if they are introduced (Shine et al., 2010). Procedures such as horizon scanning and risk screening are useful to gather the information needed to identify emerging issues (Amanatidou et al., 2012) and species with the highest likelihood of arrival and establishment, and to anticipate potential impacts (Roy et al., 2014a; Copp et al., 2016; Drolet et al., 2016; Davidson et al., 2017; Verbrugge et al., 2019). Such assessments can improve the identification, quantification and prioritization of invasive species of concern by building watch lists that identify species with the potential to impact biodiversity in a given RA area (Essl et al., 2011; Genovesi and Shine, 2011; Blackburn et al., 2014). This information is useful for prioritizing surveillance, the development of response plans, and species-specific screening tools (e.g., qPCR markers for genetic detection) (Reaser et al., 2020).

This paper outlines a horizon scanning exercise to identify potential higher risk species for the Hudson Bay Complex. This region has conditions predicted to be suitable for the establishment of some marine invasive species of concern (Ware et al., 2016; Goldsmith et al., 2018, 2020). The specific objective

of this study was to develop a ranked list of species that could be appropriate to include in watch lists for the Hudson Bay Complex. Using these rankings, it was then assessed: (1) which ecological categories (zoobenthos, phytobenthos, and zooplankton) and taxonomic groups may pose the greatest likelihood of invasion and impact; (2) which ecoregions are most likely to be sources of high-risk species for the RA area; and (3) the importance of each component in the invasion risk calculation (likelihood of invasion and ecological impact) for assessed AIS in the RA area.

## MATERIALS AND METHODS

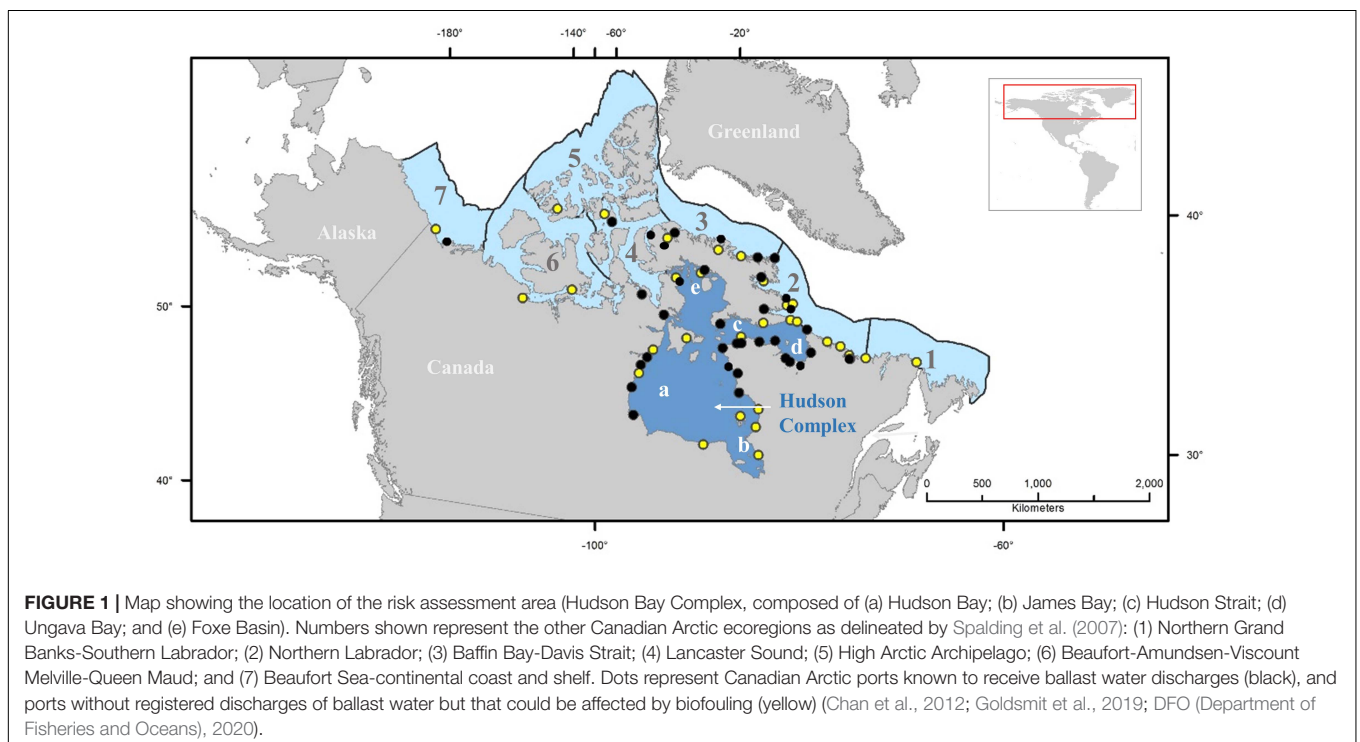
### Risk Assessment Area

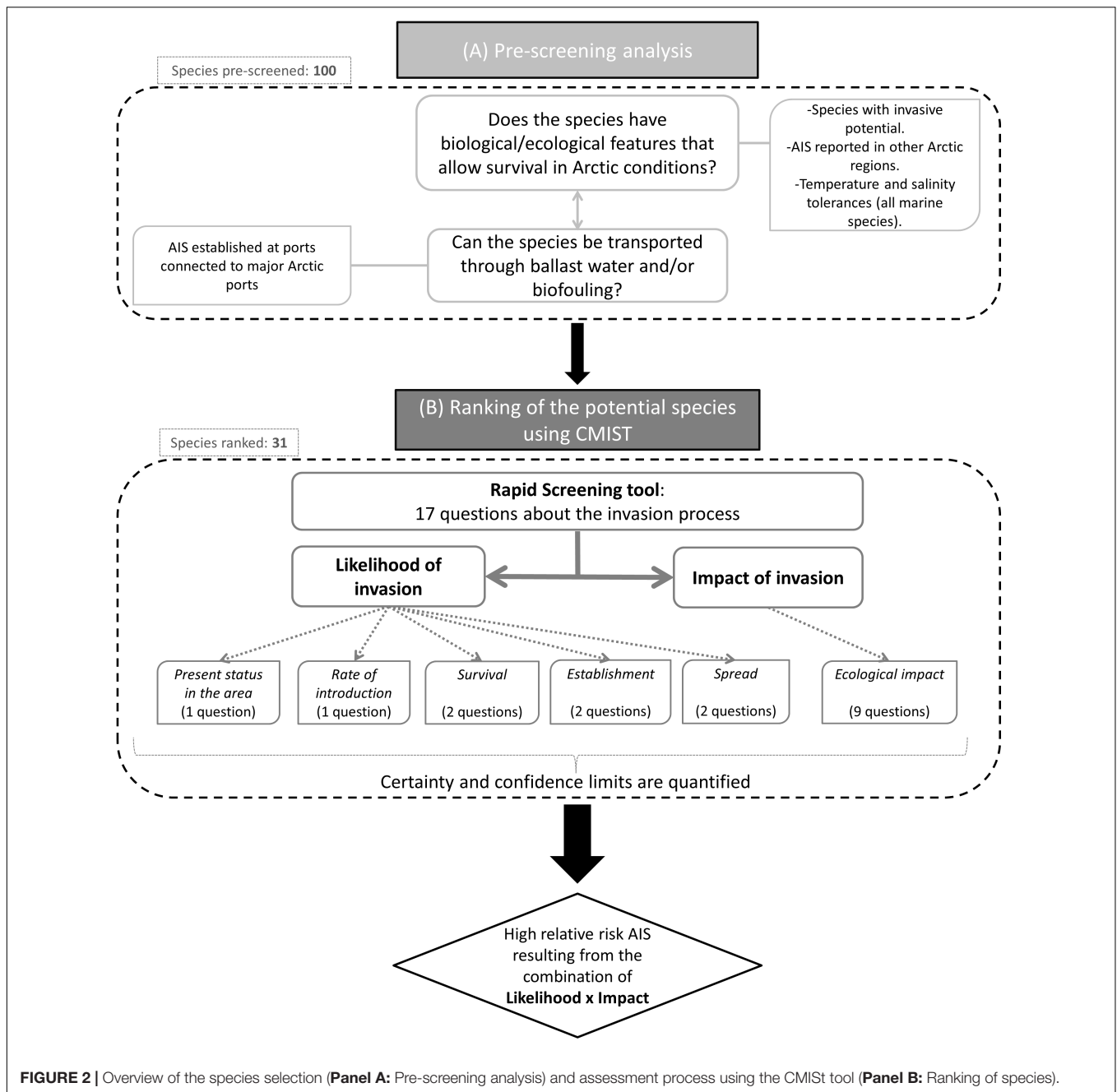
The Hudson Bay Complex is one of eight marine ecoregions of the Canadian Arctic (Spalding et al., 2007). It includes Hudson Strait, Hudson Bay, Foxe Basin, James Bay and Ungava Bay (Figure 1). It is characterized by receiving a large volume of freshwater runoff, an important penetration of Arctic marine waters into the system, and a dynamic coastal zone geomorphology (Stewart and Lockhart, 2005, and references therein). Hudson Bay is relatively shallow (150 m mean depth) (Prinsenberg, 1986) and is isolated from open ocean circulation by shallow sills; with local atmospheric conditions forcing inter-annual sea ice cover variations (Hochheim and Barber, 2014, and references therein). A wide range of habitats are available and used throughout the year by a variety of Arctic/Subarctic organisms, together with others that are only seasonal inhabitants such as migratory fishes, marine mammals and birds (Stewart and Lockhart, 2005).

The ecoregion hosts the greatest proportion of ports in the Canadian Arctic (Chan et al., 2012; Goldsmith et al., 2019; Figure 1) and the ecological risk to the area is considered high relative to other Canadian Arctic ecoregions (Stewart and Howland, 2009; Goldsmith et al., 2019) as it offers habitat suitable for potential AIS establishment now and under future global change scenarios (Goldsmith et al., 2018, 2020). The risk associated with individual discharges by international transoceanic vessels in the Canadian Arctic is high (Casas-Monroy et al., 2014), thus overall risk can be expected to increase as shipping volumes in the RA area continue to increase in the future (Judson, 2010; Étienne et al., 2013). For example, by ca. 2028 (Baffinland (Baffinland Iron Mines Corporation), 2020b), the Mary River iron ore mine will require 102 cape class ore carriers annually to arrive in ballast and load ore at Steensby Inlet in northeastern Foxe Basin if it is to meet its approved export targets (Baffinland (Baffinland Iron Mines Corporation), 2012). This is roughly 3 times the volume of ballast water currently discharged throughout the eastern Canadian Arctic. In addition, grain shipments from the Port of Churchill also resumed in 2019 and are expected to increase (Franz-Warkentin, 2019).

### Species Selection

For this risk assessment, 100 potentially invasive species were pre-screened based on their biological/ecological traits and considering Arctic environmental conditions related to their potential survival. Only species able to withstand cold temperatures and capable of tolerating brackish and marine water were selected (Figure 2A). Information on the species' potential for transport by shipping to the region was also considered. These two selection criteria were included to ensure that the





assessment was realistic in that it considered species with chances of surviving Arctic conditions and a means of anthropogenic transport to the Arctic. Data used for this pre-screening step were gathered from the published and gray literature (Hines et al., 2000; Ruiz et al., 2006; Molnar et al., 2008; Chan et al., 2012, 2016; Geller and Ruiz, 2013; Chain et al., 2016; Ware et al., 2016; Young, 2016; Turbelin et al., 2017) and global invasive species lists (National Exotic Marine and Estuarine Species Information System NEMESIS<sup>1</sup>; Invasive Species Compendium<sup>2</sup>;

the European Network on Invasive Alien Species NOBANIS<sup>3</sup>; and the Global Invasive Species Database GISD<sup>4</sup>).

A total of 39 species were thus selected for ranking with the Canadian Marine Invasive Species Tool (CMIST) (Drolet et al., 2016) to assess their likelihood of invasion and potential impacts in the Hudson Bay Complex. Only 31 ended up being completely ranked (**Table 1**) since sufficient detailed information required to answer screening questions was missing for the remaining (or closely related) species (5 phytoplankton and 3 zooplankton

<sup>1</sup> [www.invasions.si.edu/nemesis/](http://www.invasions.si.edu/nemesis/)

<sup>2</sup> [www.cabi.org/isc](http://www.cabi.org/isc)

<sup>3</sup> [www.nobanis.org/](http://www.nobanis.org/)

<sup>4</sup> [www.issg.org/database](http://www.issg.org/database)

**TABLE 1** | Species ranked using the CMIST tool.

Species	Common name	Taxa	Ecological group	Taxonomic group
<i>Amphibalanus amphitrite</i>	Striped barnacle	Crustacea	Zoobenthos	Barnacle
<i>Amphibalanus eburneus</i>	Ivory barnacle	Crustacea	Zoobenthos	Barnacle
<i>Amphibalanus improvisus</i>	Bay barnacle	Crustacea	Zoobenthos	Barnacle
<i>Austrominius modestus</i>	Australian barnacle	Crustacea	Zoobenthos	Barnacle
<i>Botrylloides violaceus</i>	Violet Tunicate	Tunicata	Zoobenthos	Tunicate
<i>Botryllus schlosseri</i>	Golden star tunicate	Tunicata	Zoobenthos	Tunicate
<i>Caprella mutica</i>	Japanese skeleton shrimp	Crustacea	Zoobenthos	Amphipod
<i>Carcinus maenas</i>	Green crab	Crustacea	Zoobenthos	Crab
<i>Chionoecetes opilio</i>	Snow crab	Crustacea	Zoobenthos	Crab
<i>Ciona intestinalis</i>	Vase tunicate	Tunicata	Zoobenthos	Tunicate
<i>Cordylophora caspia</i>	Freshwater hydroid	Cnidaria	Zoobenthos	Other
<i>Eriocheir sinensis</i>	Chinese mitten crab	Crustacea	Zoobenthos	Crab
<i>Gammarus tigrinus</i>	Tiger scud	Crustacea	Zoobenthos	Amphipod
<i>Littorina littorea</i>	Common periwinkle	Mollusca	Zoobenthos	Mollusk
<i>Marenzelleria viridis</i>	Red-gilled mudworm	Polychaeta	Zoobenthos	Other
<i>Membranipora membranacea</i>	Coffin box bryozoan	Bryozoa	Zoobenthos	Other
<i>Molgula manhattensis</i>	Sea grape	Tunicata	Zoobenthos	Tunicate
<i>Mya arenaria</i>	Soft shell clam	Mollusca	Zoobenthos	Mollusk
<i>Paralithodes camtschaticus</i>	Red king crab	Crustacea	Zoobenthos	Crab
<i>Pontogammarus robustoides</i>	Scud	Crustacea	Zoobenthos	Amphipod
<i>Styela clava</i>	Club tunicate	Tunicata	Zoobenthos	Tunicate
<i>Codium fragile</i> spp. <i>fragile</i>	Dead man's fingers	Chlorophyta	Phytobenthos	Macroalga
<i>Dumontia contorta</i>	Dumont's tubular weed	Rhodophyta	Phytobenthos	Macroalga
<i>Sargassum muticum</i>	Japanese wireweed	Phaeophyceae	Phytobenthos	Macroalga
<i>Undaria pinnatifida</i>	Wakame	Phaeophyceae	Phytobenthos	Macroalga
<i>Acartia (Acanthacartia) tonsa</i>	No common name found	Copepoda	Zooplankton	Copepod
<i>Aurelia limbata</i>	Brown banded moon jelly	Cnidaria	Zooplankton	Macrozooplankton
<i>Centropages typicus</i>	No common name found	Copepoda	Zooplankton	Copepod
<i>Eurytemora affinis</i>	No common name found	Copepoda	Zooplankton	Copepod
<i>Eurytemora carolleeae</i>	No common name found	Copepoda	Zooplankton	Copepod
<i>Mnemiopsis leidyi</i>	Warty comb jelly	Ctenophora	Zooplankton	Macrozooplankton

species). The final set of ranked species included both benthic (zoobenthos and phytobenthos) and planktonic (zooplankton) organisms that could be transported by ship traffic, either in ballast water or as biofouling. Of the 31 species selected for ranking, three are established in the RA area: *Aurelia limbata*, *Dumontia contorta*, and *Eurytemora affinis* (Table 1).

## Risk Assessment Using CMIST

CMIST is a screening-level RA tool that uses documented information and expert opinion to semi-quantitatively assess the risk of aquatic non-indigenous species (Drolet et al., 2016) (for both species known to be invasive elsewhere in the world or not). It consists of 17 questions related to the likelihood and impact of invasion (hereafter, Invasion and Impact, respectively). Each question is scored, and a level of certainty for each questions incorporated into final score values. It has been applied to the east and west coasts of North America to assess the risk of single (Moore et al., 2018) or multiple (DFO (Department of Fisheries and Oceans), 2017; Therriault et al., 2018) species, and has been shown to provide accurate predictions of invasive species establishments and impacts (Ogilvie, 2017). Questions

relate to the present status of the species in the area of interest, rate of introduction, survival, establishment, spread, and negative ecological impacts (Figure 2B). Each question is scored from 1 (low) to 3 (high). Mean values of scores are calculated for Invasion (questions 1 to 8) and Impact (questions 9 to 17). These means are then multiplied to yield a final risk score per species that can range from 1 (lowest) to 9 (highest). In this study, CMIST scores were assigned by assessors based on a combination of expert knowledge and the best-available data for each species assessed (even information on closely related species can be used). CMIST also scores the certainty related to each question score, from 1 (low) to 3 (high), to account for confidence on the scoring according to the quality of information available at the time of assessment. To adjust certainty and aid interpretation, a Monte Carlo randomization procedure is used to generate upper and lower 95% confidence limits for risk scores (for details on calculation of mean adjusted values, refer to Supplementary Material 2 in Drolet et al., 2016). Mean adjusted values of Invasion and Impact, and mean CMIST scores were analyzed to identify highest risk species and ecological/taxonomic groups. Species with the highest relative risk (HRR species) were

defined as those scoring  $\geq 2.0$  in both risk components (adjusted Invasion and Impact) (i.e., all species that fell in the upper right quadrant of the heat matrix, **Supplementary Figure 1**).

Information used to answer the CMIST questions for each species was drawn from published articles, government reports, gray literature, and global invasive species websites, as described above. Scores were consensus-based, with all authors assessing and participating in risk scoring for all CMIST questions. Note that the ecological impacts included in the analysis are those considered to negatively impact ecosystems; potential positive impacts, such as establishment of new fisheries resources, were not considered.

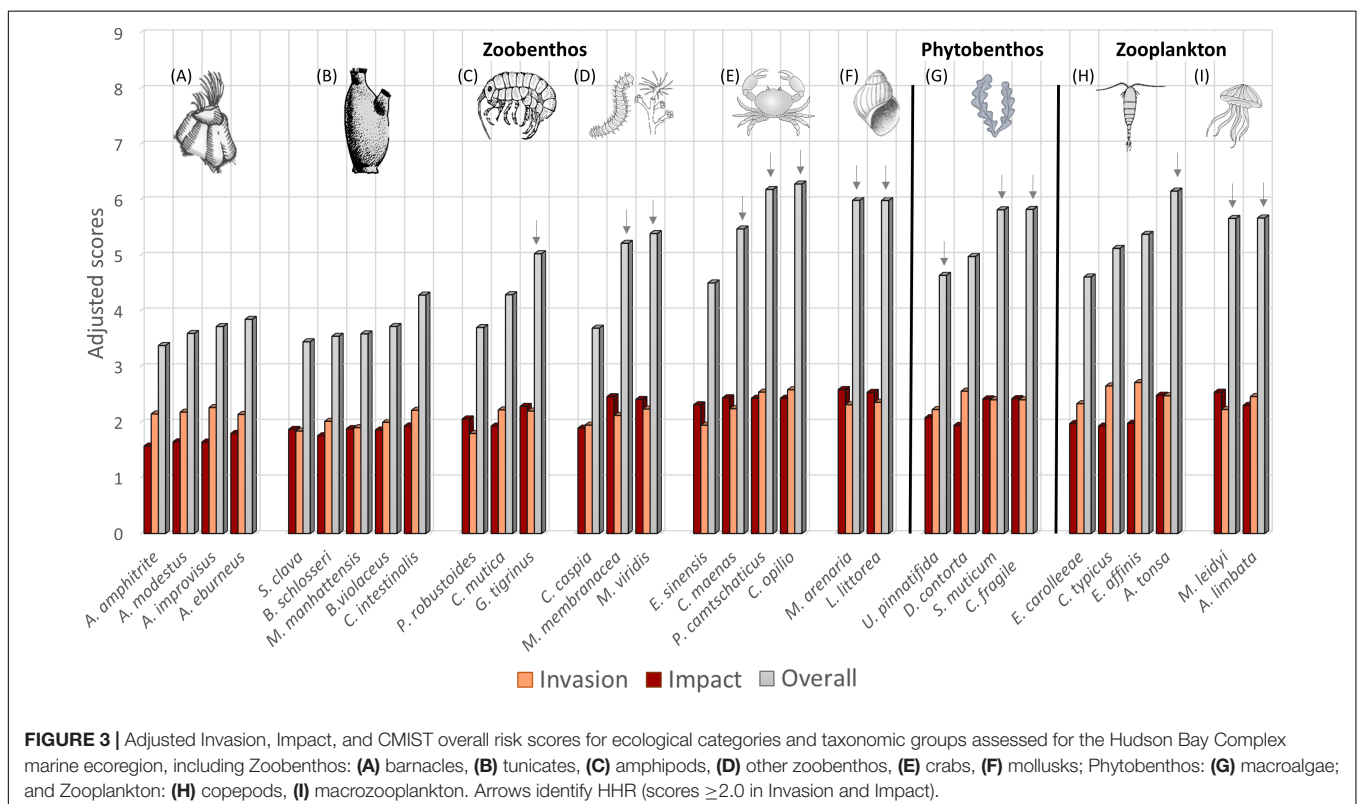
Some CMIST questions were modified for assessment in an Arctic environment. For example, for Question 16, ‘What level of impact could the species have on aquaculture and commercially fished species in the assessment area?’, subsistence fisheries were considered as they are particularly important in Arctic regions, whereas aquaculture is not. Interpretation of some questions was also modified from the original CMIST guidance to provide clearer direction for scoring, for example: (i) Question 2 (related to arrival): scores were adapted according to the number of potential vectors and known distribution of the species in connected ecoregions, (ii) Question 13 (related to diseases and parasites): additional guidance on the presence of mechanisms for arriving with the host was added, and (iii) Question 14 (related to hybridization): modifications related to the presence of known native species in the same genus were added (details given in **Supplementary Table 1**). Refer to Drolet et al. (2016) to see general guidelines for CMIST.

## Horizon Scanning Analysis With HRR Species and Source Ecoregions

Distribution of HRR species richness among ecoregions was calculated and plotted on a global map. Both known native and invaded ranges were included to evaluate the number of HRR species in each source ecoregion. Connectivity between the RA area and source regions was examined at the vessel-level according to last port of call and at the tank-level with respect to ballast origin (which may differ from the last port of call) from international and domestic ports. This information was obtained from the shipping database used in Goldsmith et al. (2019) and included last port of call and ballast water source of vessels that visited Hudson Bay Complex ports over a 10-year period (2005–2014). The proportion of connected ports that occurred within ecoregions containing HRR species was calculated, as were the proportion of discharged ballast and arrivals that originated from those ecoregions.

## RESULTS

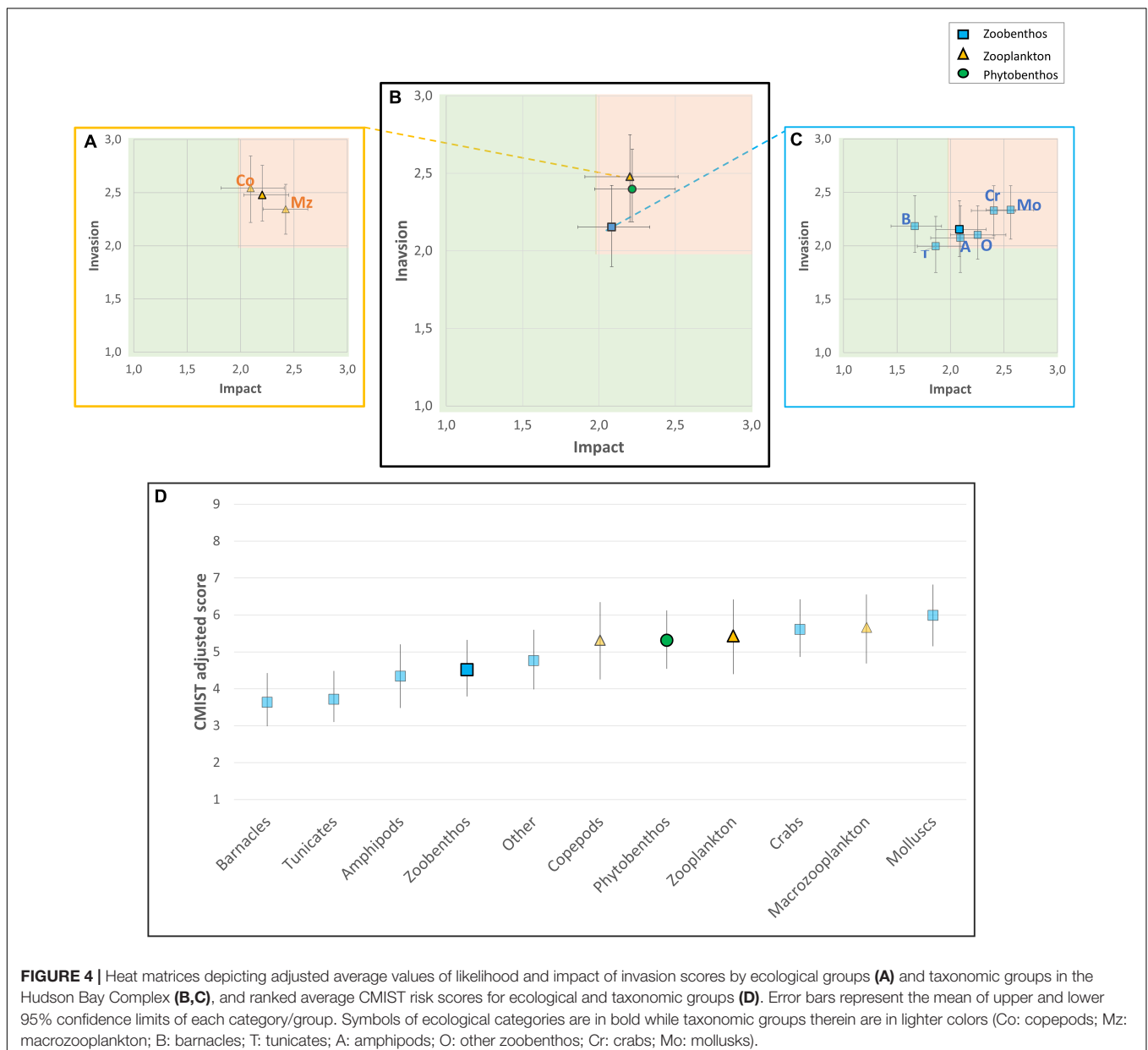
For the 31 species assessed, CMIST adjusted overall scores ranged from 3.38 to 6.28 (**Figure 3**). A total of 14 HRR species was identified for the Hudson Bay Complex: (1) *Chionoecetes opilio*; (2) *Paralithodes camtschaticus*; (3) *Acartia (Acanthacartia) tonsa*; (4) *Mya arenaria*; (5) *Littorina littorea*; (6) *Codium fragile* spp. *fragile*; (7) *Sargassum muticum*; (8) *Aurelia limbata*; (9) *Mnemiopsis leidyi*; (10) *Carcinus maenas*; (11) *Marenzelleria viridis*; (12) *Membranipora membranacea*;



(13) *Gammarus tigrinus*, and (14) *Undaria pinnatifida* (**Figure 3**, **Supplementary Figure 1**, and **Table 1**). This list includes almost half of the species that were pre-screened from zoobenthos and zooplankton ecological categories and three of the four species in the phytobenthos category. Note that different combinations of Invasion and Impact scores may yield similar CMIST risk scores (**Figure 3**). For example, *D. contorta* and *G. tigrinus* have similar CMIST risk scores (4.98 and 5.03, respectively), but greater differences in their Invasion (*D. contorta* = 1.95 and *G. tigrinus* = 2.28) and Impact scores (*D. contorta* = 2.56 and *G. tigrinus* = 2.20).

The contributions of Invasion and Impact for individual species may be seen when plotted against each other in a heat matrix, highlighting those for which both components have

scored high (upper right quadrant, **Supplementary Figure 1**) and in graphic form showing overall adjusted CMIST scores (**Supplementary Figure 2**). The same was done at the ecological and taxonomic levels by grouping species score values for the different categories (**Figure 4**). Variation in scores for zoobenthos is greater than that for the other two ecological categories as mean taxonomic group values vary greatly (differences of up to 2.35 on mean taxonomic group scores for zoobenthos, while a variation of only 0.35 was observed between zooplankton taxonomic group means) (Note that there was only one taxonomic group for phytobenthos) (**Figures 3, 4**). This variation in individual scores seems to be somewhat related to ecological category size. In general, zooplankton and phytobenthos have similar mean values for Invasion and Impact, whereas zoobenthos have a wider range



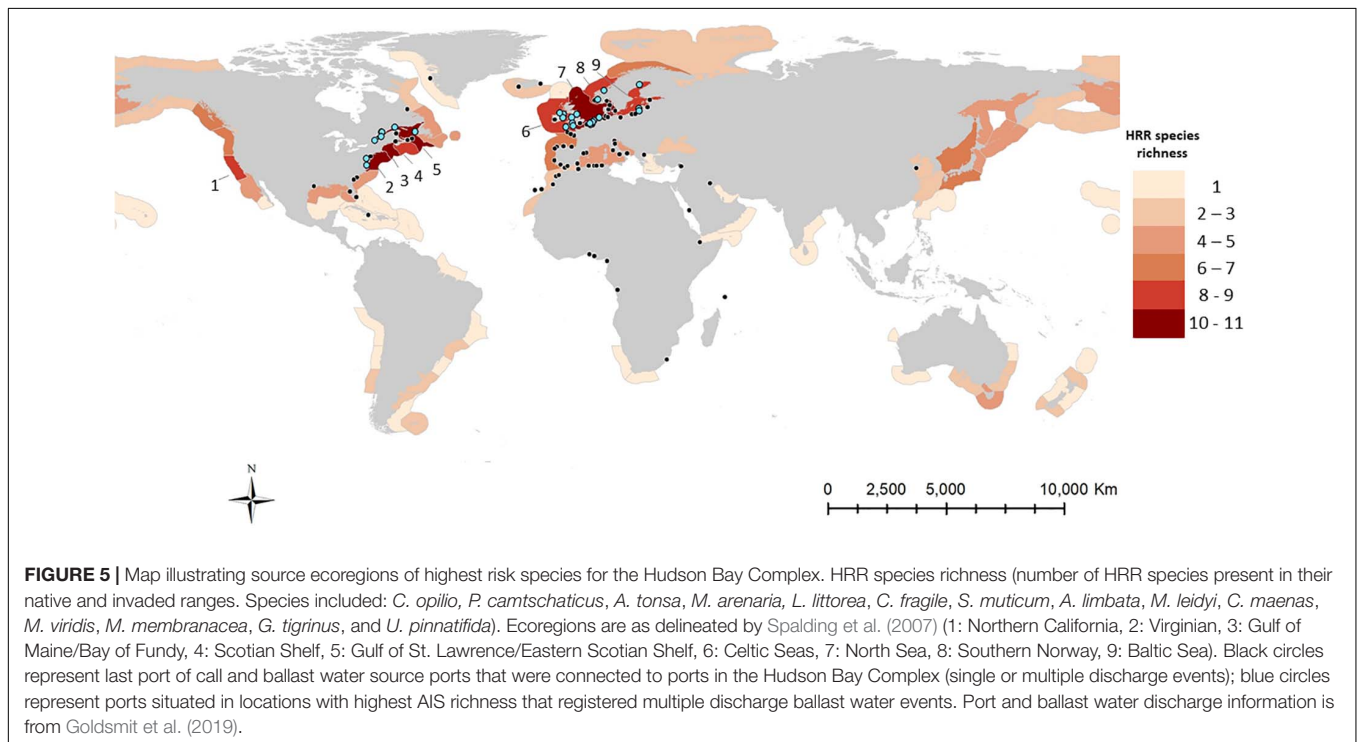
of mean values, which is a function of differences in taxonomic group characteristics (Figures 3, 4). For zoobenthos, crabs and mollusks had the highest mean combination of Invasion and Impact, while tunicates and barnacles had the lowest (Figure 4 and Supplementary Figure 2). Variation in Invasion and Impact among taxonomic groups may have differing effects on final CMIST scores (as was also seen at the species-level). For instance, barnacles had higher Invasion but lower Impact likelihoods relative to tunicates (Figure 4C), resulting in the groups ending up with very similar mean CMIST scores (Figure 4D).

In total, the native and invaded distributions of the 14 HRR species span 60 of the global marine ecoregions (Figure 5). Up to 11 of the identified HRR species may be found in each of these ecoregions (Figure 5). Of the 60 ecoregions, 22 are connected to the RA area through single or multiple ballast water discharges or vessel arrivals (Figure 5). The richest sources of HRR species for the Hudson Bay Complex were on the east and west coasts of the North Atlantic (Figure 5). The principal ecoregions showing the highest HRR species richness were the Virginian, Gulf of Maine/Bay of Fundy, Scotian Shelf, and Gulf of St. Lawrence/Eastern Scotian Shelf in the Northwest Atlantic, and the Celtic and North Seas in the Northeast Atlantic (Figure 5). These ecoregions include 50.4% of the ports that are connected to the RA area by domestic and international vessels that discharged ballast water at ports in the Hudson Bay Complex between 2005 and 2014 (Figure 5). Single and multiple discharges from these source ecoregions represent 79.3% of the total ballast water discharged and 51.4% of arrivals in the RA region during this time period. The Northern California ecoregion also supports 8 of the HRR species but it does not have ports directly connected by shipping to the Hudson Bay Complex.

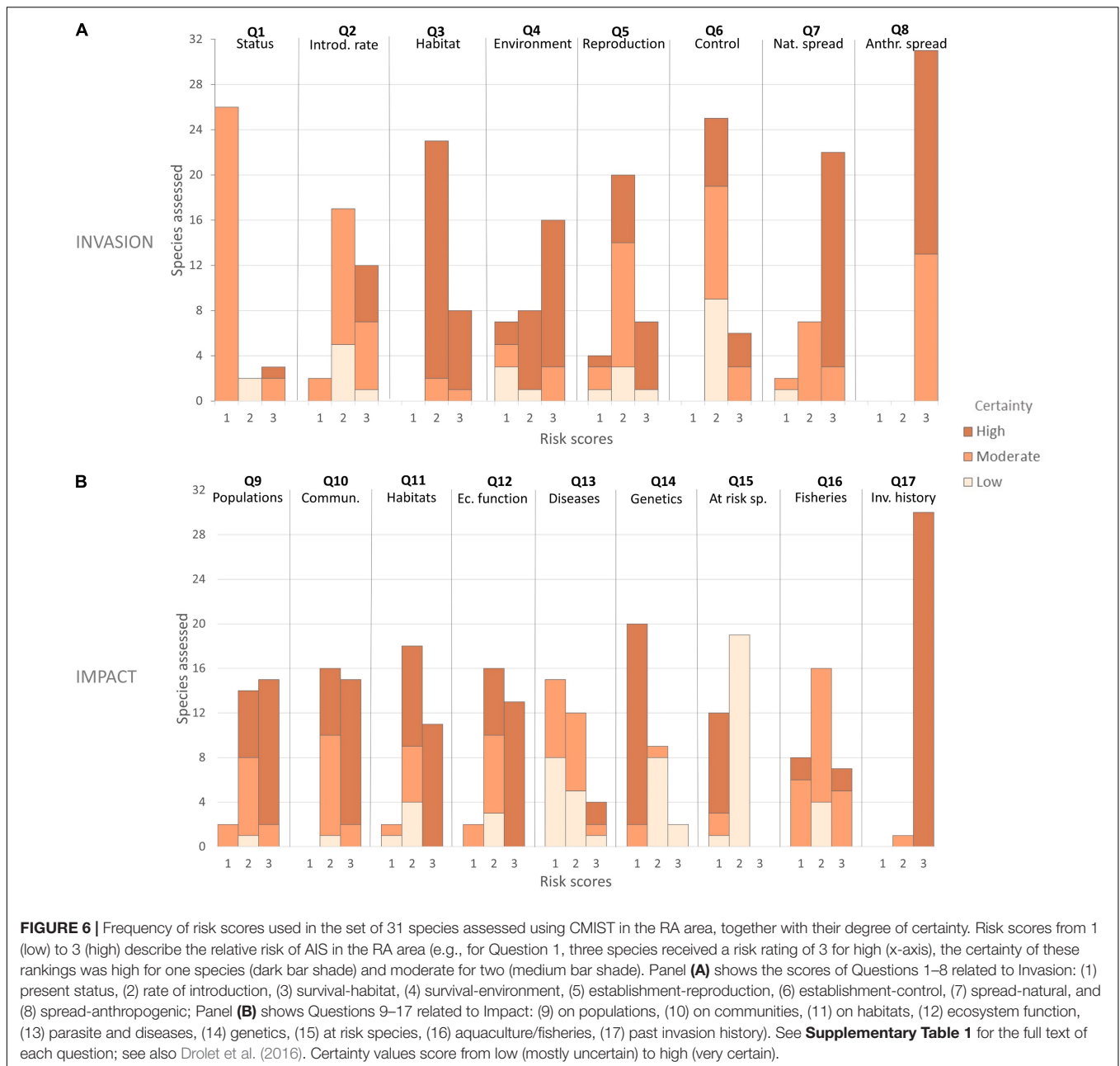
Overall, considering the ensemble of questions for the 31 species assessed, about 20% of the CMIST question results were scored as low, 42% moderate, and 38% high (corresponding to risk scores of 1, 2, and 3 respectively) (Figure 6 and Supplementary Table 1). The degree of certainty related to these scores generally ranged from moderate to high (Figure 6). Questions 8 (related to anthropogenic dispersal) and 17 (related to known invasiveness of the species) scored the highest for all species (and generally with high certainty), since these species are known AIS that may be transported by anthropogenic vectors. In contrast, Question 1 (related to the presence of the species in the RA area) scored the lowest (with moderate certainty), since data on species presence in the RA region is limited and because invasions have likely been limited to date, thus most species are not known AIS for the region (Figure 6).

## DISCUSSION

This study highlights AIS that could be of major concern for the Hudson Bay Complex and their potential main source regions through the first application of the rapid screening approach, CMIST, in a polar RA area. Although all species included in the assessment were pre-selected based on their ability to withstand colder temperatures and their potential for transport in pathways with connections to the Hudson Bay Complex, screening with CMIST identified a subset of species with higher relative risk (14 of the 31 assessed species). The approach of averaging and assembling analyses to examine results from an ecological category perspective revealed that zooplankton and phytoplankton had similar high Invasion, Impact, and overall







risk scores. In contrast, the average risk values of zoobenthos were lower when considered collectively as a group, but there was high inter-taxonomic grouping variability. In general, taxonomic groups such as crabs, mollusks, macrozooplankton, and macroalgae had relatively higher risk for invasion in the Hudson Bay Complex. Distributions of higher relative risk species were concentrated mainly along the east and west coasts of the North Atlantic Ocean, which have a high proportion of ports connected to the Hudson Bay Complex by shipping and could therefore serve as important source regions for AIS.

This study incorporates two novel approaches in the way the CMIST tool is applied. The first relates to the ecological and taxonomic groups assessed. CMIST has been applied previously

to invertebrates (mainly benthic) (Drolet et al., 2016; Moore et al., 2018; Therriault et al., 2018), but this is the first time it has been applied to other groups, including phytozoobenthos and zooplankton. This is a reasonable approach since the CMIST questions are not taxon-specific but, rather, relate directly to the invasion process and known impact of the assessed species (DFO (Department of Fisheries and Oceans), 2015; Drolet et al., 2016). The second approach is related to the use of mean scores across the species assessed to analyze patterns by clusters of ecological and taxonomic groups. Risk assessment of taxonomic groups has been done at regional (Roy et al., 2014a; Verbrugge et al., 2019) and global scales, emphasizing AIS impact by taxonomic and functional groups (Gallardo et al., 2016a; Anton et al., 2019),

but has not been plotted or analyzed using the combination of likelihood and impact of invasion. CMIST scores were also used to highlight common source regions and connected ports for HRR species. This study thus shows new ways of applying and analyzing CMIST results to evaluate ecological- and taxa-specific patterns.

## HRR Species in the Hudson Bay Region

Fourteen invasive marine species were identified as posing the highest relative risk to the Hudson Bay Complex. In this context, species and groups of particular note included crabs (green crab *C. maenas*, snow crab *C. opilio*, and red king crab *P. camtschaticus*), mollusks (common periwinkle *L. littorea*, and soft-shell clam *M. arenaria*), macrozooplankton (warty comb jelly *M. leidyi* and brown banded moon jelly *A. limbata*), and macroalgae (dead man's fingers *C. fragile* spp. *fragile*, Japanese wireweed *S. muticum*, and wakame *U. pinnatifida*). Of these, only one species, *A. limbata*, is already established in the RA area. These findings are corroborated by environmental niche models and ecophysiological threshold models, which have shown that the majority of HRR species are predicted to find suitable habitat in some regions of the RA area under current and/or projected climate change scenarios (Ba et al., 2010; Crafton, 2014; Ware et al., 2016; Goldsmith et al., 2018, 2020; Lins et al., 2018). Additionally, a species-specific ecological risk assessment of the Canadian Arctic using *L. littorea* and *M. arenaria* showed that ports situated in the Hudson Bay Complex (Churchill and Deception Bay), are presently under moderate to high relative risk of invasion given the current vessel traffic in the region, particularly with respect to domestic vessels (Goldsmith et al., 2019).

HRR species are presently distributed in regions that are well connected by shipping traffic to the RA area. These pathways provide ongoing opportunities for their transport into the RA area, making them so called “door knockers” (future invasive species identified in horizon scanning exercises that have not yet been introduced but that could be expected to arrive in the near future) (Roy et al., 2014b; Boršić et al., 2018). These door knockers are presently distributed and highly concentrated in ecoregions situated along the east and west coasts of the North Atlantic Ocean. Both coasts have some of the highest global AIS richness (Gerald et al., 2020), and include organisms in both their native and invaded ranges. Potential transport of these species between source ecoregions and the Hudson Bay Complex is further strengthened by the presence of numerous connected ports and the fact that there have been multiple ballast water discharges into the RA area from nearly half of those. This connectivity is likely to further increase given that the number of voyages to the Arctic has increased over the last few years (Dawson et al., 2018; Lasserre, 2019) and is predicted to continue rising under future climate change scenarios (Smith and Stephenson, 2013; Melia et al., 2016; Andrews et al., 2018).

Door knocker species have already been found in ships visiting Canadian Arctic ports. *A. tonsa*, for example, was found in ballast water samples from vessels arriving in Deception Bay (Dispas, 2019). The same study found *A. limbata* at the port of Churchill in 2015 (Dispas, 2019) while studies that used

metabarcoding sequencing reported signals of *M. arenaria* and *A. limbata* in Churchill (Chain et al., 2016; Grey et al., 2018). Some of these species are already established in other regions of the Arctic, including *C. opilio* in Barents and Kara seas, *P. camtschaticus* in Barents Sea, *M. arenaria* and *C. fragile* spp. *fragile* on the Iceland Shelf, and *M. manhattensis*, *M. viridis* and *S. muticum* in the Norwegian Sea (Orlov and Ivanov, 1978; Berger and Naumov, 2002; Sokolov and Milyutin, 2006; Shakirova et al., 2007; Falk-Petersen et al., 2011; Gederaas et al., 2012; Sundet, 2014; Thorarinsdottir et al., 2014; Zimina, 2014; Dvoretzky and Dvoretzky, 2015; Cohen, 2016; Chan et al., 2019; Espelien, 2020). Door knocker species should be taken seriously considering connectivity due to shipping and the fact that some are already established in other Arctic regions. Additionally, two of these door knocker species (*C. maenas* and *U. pinnatifida*), are also listed as potential species that could threaten biodiversity and ecosystems in another polar environment (the Antarctic Peninsula) (Hughes et al., 2020).

## Ecological Categories and Taxonomic Groups

Assessment of the broader phytobenthos and zooplankton categories yielded similar, high overall risk scores, while zoobenthos was lower but with great inter-group variability, depending on taxonomic group. The highest relative risk scores calculated for the Hudson Bay Complex were within the taxonomic groups for crabs, mollusks, macrozooplankton, and macroalgae. These findings are consistent with studies that have identified crabs and mollusks as the two dominant groups of marine invasive species (Molnar et al., 2008; Ruiz et al., 2015), and crustaceans as one of the most successful invasive species groups (Hänfling et al., 2011). The invasive success of these groups has been attributed to their generalist (eurytolerant and omnivorous) and r-selected life-history characteristics (Hänfling et al., 2011 and references therein). Shipping has been highlighted as one of the most important pathways of introduction, both via ballast water and biofouling, for all these taxonomic groups (Oliveira, 2007; Molnar et al., 2008; Hänfling et al., 2011; Ruiz et al., 2015).

Impacts of invasive crab, mollusk, macrozooplankton, and macroalgae species may be substantial and significantly affect various levels of ecosystems. Invasive crustaceans may trigger cascading effects that affect ecosystem services (e.g., biodiversity, water quality) by changing energy fluxes and nutrient cycles (Hänfling et al., 2011 and references therein). Crabs and mollusks are among the groups that have been the cause of large overall declines in the number of native taxa (Anton et al., 2019). Macrozooplankton species may also impact various levels of the food web. For example, predation on fish eggs, fish larvae, and zooplankton by *M. leidyi* as well as competition with the latter 2 groups has caused the collapse of planktivorous fish stocks in the Baltic Sea (Daskalov et al., 2007; Oguz et al., 2008; Ojaveer et al., 2018). Predatory marine invasive species are of particular concern as they may have stronger effects on native communities and lead to larger ecological impacts than AIS belonging to other trophic levels (Gallardo et al., 2016a; Anton et al., 2019). And lastly, invasive macroalgae can change richness and diversity

of native species, decrease the cover of other macroalgae, and even change the habitat since they may modify the existing architectural structure (Schaffelke et al., 2006 and references therein; Wallentinus and Nyberg, 2007). In addition to ecological impacts, introductions of species from these groups have resulted in substantial economic impacts (Pimentel et al., 2005; Colautti et al., 2006; Lovell et al., 2006; Marbuah et al., 2014).

## Risk Assessment Components, Horizon Scans, and Watch Lists

Across the complete suite of species assessed, likelihood of invasion ranged from moderate to high for most species, due, in part, to the fact that all are known AIS that may be transported via ballast water and/or biofouling. However, this risk component was likely affected by the pre-screening process that selected cold-tolerant species. This risk component may also have been influenced by the fact that few species were established in the RA area, although scores for the three that established varied widely and did not differ noticeably from non-established species, suggesting this was not the case. Likewise, scoring of impact of invasion was likely affected by the fact that all assessed species are known invaders from other regions of the world, with considerable information in the literature about their known negative ecological impacts. Nevertheless, information about ecological effects of invasive species in the marine ecosystem is limited compared to other ecosystems (Crystal-Ornelas and Lockwood, 2020). Given this, and that most of these species are not yet present in the RA area, certainty scores varied widely, depending on the question and species assessed. While impacts caused elsewhere can be a good predictor of the potential impact in a new region (Hayes and Barry, 2008), environmental similarity must be considered, together with habitat characteristics and species composition of each ecoregion (Kumschick and Richardson, 2013). The need to improve the accuracy and consistency of impact scoring in risk assessments has been identified previously (Kenis et al., 2012; Kumschick and Richardson, 2013) and is an important consideration, particularly when comparing across studies. Accordingly, some modifications from the original CMIST guidance were made to better assess regional impact. Nevertheless, CMIST can be particularly informative in assessing relative risk to prioritize marine invaders that are not yet reported in a particular RA area (DFO (Department of Fisheries and Oceans), 2015). CMIST also has the advantages of transparency, consistency, and flexibility to allow for continuous improvement when compared to other screening tool methods (Srėbaliėnė et al., 2019).

Certainty, which is influenced by the quality and quantity of information, was incorporated into the adjusted values and confidence limits for the score for each species. An advantage of CMIST is that it allows certainty to be quantified and translated into confidence limits, a feature most risk assessment tools lack (Koop et al., 2012; Drolet et al., 2016). This is achieved by predicting the probability of possible combinations of score and certainty to a different answer than an assessor might have provided and generating the range of potential

scores associated with the 95% confidence limits (Drolet et al., 2016, 2017). This characteristic helps improve interpretation and usability in management (DFO (Department of Fisheries and Oceans), 2015). While CMIST may be overparameterized, it is much less-so than other tools (DFO (Department of Fisheries and Oceans), 2015; Drolet et al., 2017), and its favorable points (e.g., performance, low inter-assessor variability, distinction between invasion elements, certainty quantification, etc.) make it a good option to assess the risk associated with door knocker species that could be introduced to the Hudson Bay Complex.

Over the past decade, European countries have been undertaking horizon scans to produce watch lists to highlight the principal species of concern for their regions (e.g., Shine et al., 2010; Roy et al., 2014b, 2015; Gallardo et al., 2016b; Matthews et al., 2017; Carboneras et al., 2018; Paganelli et al., 2018; Peyton et al., 2019; Killi et al., 2020). These efforts are related to the objectives of a European Union regulation (1143/2014) and the Commission Delegated Regulation (EU) No 2018/968 (2018), which are to control/eradicate priority species and prevent the introduction and establishment of new invasive species by managing pathways of introduction. This states that species to be added to the “Union list” must have, as a precondition, been evaluated through risk assessment (European Union, 2018). These types of regulations are not in force under Canadian legislation, making all efforts to identify potential invasive species using science-based risk assessment tools, such as in the present study, more valuable. However, under the International Convention for the Control and Management of Ship’s Ballast Water and Sediments, adopted by the International Maritime Organization (IMO) in 2004 and which entered into force in September 2017, newer vessels originating from outside of Canada’s Exclusive Economic Zone are required to manage their ballast water through treatment to reduce risks for species introductions (IMO (International Maritime Organization), 2021). These measures should help prevent the arrival of new species through this particular vector.

## CONCLUSION

Three of the 14 door knockers species identified in this assessment (*C. maenas*, *M. leidyi*, and *U. pinnatifida*) are included in the Global Invasive Species Database’ list of “100 of the World’s Worst Invasive Alien Species”<sup>5</sup> (Lowe et al., 2000). Actions to prevent their arrival and establishment should be undertaken. CMIST analysis provided a standardized structure for interpreting ecological information from the Hudson Bay region in relation to species requirements and potential effects. This tool can also be used to develop watch lists for management actions based on the relative ranking of species in other regions [e.g., black and gray watch lists; see Essl et al. (2011) and Blackburn et al. (2014)]. To be useful, this type of assessment to identify potential threats must be followed by appropriate actions (Sutherland and Woodroof, 2009).

<sup>5</sup>[http://www.iucngisd.org/gisd/100\\_worst.php](http://www.iucngisd.org/gisd/100_worst.php)

The high-risk species identified here are of particular concern and managers should mitigate risks by taking preventative actions, monitoring for arrivals, and planning for early responses if initial measures fail. Management of invasive species can have a range of economic benefits, including protecting biodiversity and maintaining ecosystem health (Hanley and Roberts, 2019). The effects of invasive species on native diversity in aquatic ecosystems and remote regions with low accessibility, such as the Canadian Arctic, are poorly understood (Florenco et al., 2019). Anticipating and preventing potential AIS establishment and associated environmental and economic costs will be increasingly important as climatic conditions change and shipping traffic increases.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

JG, CM, and KH contributed to the conceptualization. JG performed the formal analysis, visualization, and wrote the original draft. KH and CM obtained funding for the work and provided resources and supervision for the project. CM, DS, and KH reviewed and edited it. All authors contributed to the methodology (risk assessment scoring) and the investigation, read and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2021.627497/full#supplementary-material>

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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