UQAR

Université du Québec
à Rimouski

BENTHIC NON-INDIGENOUS SPECIES IN PORTS OF THE CANADIAN ARCTIC: IDENTIFICATION, BIODIVERSITY AND RELATIONSHIPS WITH GLOBAL WARMING AND SHIPPING ACTIVITY

LES ESPECES ENVAHISSANTES AQUATIQUES DANS LES COMMUNAUTES BENTHIQUES MARINES DES PORTS DE L'ARCTIQUE CANADIEN: IDENTIFICATION, BIODIVERSITE ET LA RELATION AVEC LE RECHAUFFEMENT CLIMATIQUE ET L'ACTIVITE MARITIME

Thèse présentée

dans le cadre du programme de doctorat en océanographie

en vue de l'obtention du grade de *philosophiae doctor*, océanographie

PAR

© JESICA GOLDSMIT

Avril 2016

Composition du jury :

Dr Gesche Winkler, président du jury, Université du Québec à Rimouski

Dr Philippe Archambault, directeur de recherche, Université du Québec à Rimouski

Kimberly Howland, codirectrice de recherche, Pêches et Océans Canada

Ricardo Sahade, examinateur externe, Universidad Nacional de Córdoba (Argentina)

Dépôt initial le 5 novembre 2015 Dépôt final le 21 avril 2016

A mi querido compañero de la vida, que me enseñó a ver el mundo desde la felicidad.

A mi madre, por siempre confiar en mí y apoyarme en todos mis proyectos.

"*La vida tiene profundidades que las palabras no alcanzan a sondar*" **Carlos Gonzalez**

REMERCIEMENTS

Merci à Philippe Archambault de m'avoir donné la chance de changer ma vie avec ce projet. J'ai apprécié ton soutien et ta confiance. Tu m'as donné une grande liberté d'action et de créativité pour le travail et pour des activités avec le groupe du laboratoire. Merci d'avoir cru en moi. Merci pour ta joie et ton sens de l'humour. Tu le sais déjà : je vais te suivre n'importe où, même à Vancouver!

Thank you Kim for your support and trust, for making me use all my neurons and always ask me questions that make me think. Thank you for opening the doors of your house for every time I went to Winnipeg. Thank you for believing in me.

Merci à Chris Mckindsey et à André Rochon, membres du comité de thèse, pour votre participation, pour votre temps et vos commentaires pendant tout mon cheminement. Merci Gesche pour ton temps comme présidente du jury de thèse et pour ta bonne humeur constante.

Ricardo Sahade, el Ricky… gracias infinitas por nunca dejar de creer en mí, hiciste que mi vida cambie y de un giro de 360°. Siempre con la palabra justa, aconsejandome desde el primer año de universidad. Fuiste, sos y seguirás siendo mi mentor. Qué mejor cierre de una etapa como ésta teniéndote como miembro externo de mi jurado de tesis. Un placer saberte leyendo el contenido de estas páginas y poder tener tus comentarios. Sabes que cada vez que esté ante una página en blanco, con el cursor titilando antes de comenzar un nuevo texto, una nueva etapa, siempre pensaré en tus palabras.

Merci à tous les gens de l'ISMER. Merci à l'équipe du laboratoire de benthos, merci pour chaque « sugar fix », pour chaque fête de Noël. Merci infiniment à Lisa Tréau et à Laure de Montety pour votre patience et pour m'avoir appris tout le fonctionnement du labo. Merci Cindy Grant d'avoir régulièrement organisé des activités et pour tes idées originales. Merci à toutes les filles du labo, et bien sûr… merci David Beauchesne pour le temps consacré à parler avec moi : merci pour ta patience et pour le partage fréquent de moments de réflexion.

Thank you to all the people that helped in the field and in the lab. Without you, I would be still sorting samples at the lab now. Great thanks to Kristen Aider for invaluable help in the project, and especially for her friendship and her beautiful laughter.

I want to acknowledge the Canadian Aquatic Invasive Species Network (CAISN) and the Natural Sciences and Engineering Research Council (NSERC) for every opportunity they gave me in my career. From the scholarship to do my project, to all the other opportunities that supported me (courses, congresses, internship). I also want to acknowledge Québec-Océan for support during these four years.

Merci à tous mes amis que j'ai rencontré ici à Rimouski. Merci à Sahar Mejri qui a été mon amie dès le premier jour, merci pour tes paroles et pour ton écoute. Merci « mon ange » Oscar Casas-Monroy pour ton amitié et pour ton soutien moral depuis que je suis arrivée ici. Merci à toutes les personnes du local O-262 et à toutes les personnes qui sont passées à l'ISMER et qui maintenant sont des amis de partout dans le monde : Paqui, Alejandro, Anni, Olivier, Vane, Loli, Ana, Sabri, Grisel, Adriana, Maga. Merci Amin pour ton amitié. Merci Nathalie Landreville de m'avoir aidée à parler et à écrire en français, et pour tes beaux rires contagieux!

A toda mi familia, especialmente mi madre quien siempre creyó en mí y mi tía Bety por el apoyo incondicional. Gracias a la familia Vuirli por el apoyo no sólo hacia mí, sino también por el apoyo incondicional a Nacho con todas sus locuras. Gracias a mis amigas del secundario y de la facu (Roxy, Romi, Euge, Ando, Bel, Fer).

Gracias a mi familia elegida de estas latitudes. Ire y Gus, no sé qué hubiera hecho sin ustedes estos años. Gracias por las clásicas pausas mañaneras de mates y por estar siempre, aun así a pesar de la "jugarreta cósmica". Gracias Ire y Ana por su amistad y por los almuerzos semanales en español, momento único y esperado durante cada semana. Gracias Dani y Cris, por las numerosas cenas compartidas y las ayudas incondicionales y por ser

tan buenas personas. Gracias infinitas a toda la comunidad argentina de Rimouski, no hubiera sido para nada lo mismo esta experiencia sin ustedes.

Gracias Nacho, gracias por sumarte a esta locura y hacer que sea aún más loca todavía. Quién diría que nuestras vidas cambiarían tanto por haberme sentado adelante tuyo. Gracias por estos años y por el resto de los años de nuestras vidas. Rimouski (ese lugar de nombre raro) pasa a ser parte de nuestra historia de vida para siempre. Gracias por esta familia que estamos construyendo. Y Pimpollo, gracias por venir a nuestras vidas, por dejarme trabajar mientras estas creciendo adentro mío y por entender desde tan chiquito las locuras de tu madre.

RÉSUMÉ

Le changement climatique entraîne des variations dans les conditions environnementales, notamment sur le plan de la température et du couvert de glace dans les régions de hautes latitudes telles que l'Arctique canadien. Les modèles prédictifs et les évaluations de risques représentent des outils essentiels pour comprendre les changements en cours et prévus et leurs impacts sur les régions côtières. Il est primordial de prévoir comment l'introduction de nouvelles espèces va interagir avec des moteurs de perturbations tels que le changement climatique, l'activité de navigation et l'augmentation de l'exploitation des ressources, car ces espèces peuvent engendrer un coût économique et écologique élevé. Pour toutes ces raisons, il est important d'évaluer les risques actuels et futurs associés aux espèces nouvellement introduites dans une région comme l'Arctique canadien. L'objectif principal de la présente thèse est de caractériser la biodiversité indigène et non indigène des invertébrés benthiques dans des ports de l'Arctique canadien, où le risque d'introduction est le plus élevé, et d'évaluer le risque global lié à d'éventuelles espèces aquatiques envahissantes dans un scénario de réchauffement global et de navigation accrue.

Le chapitre 1 fait état de la collecte, de la compilation et de la comparaison d'information historique et contemporaine sur la biodiversité côtière. Ce chapitre contribue à l'amélioration des connaissances de base sur la présence et la distribution des taxons benthiques le long des principaux ports de la côte de l'Arctique. En raison de l'effort d'échantillonnage accru dans la région, un total de 236 espèces et genres ont été identifiés, dont 7 à 15 % sont considérés comme des nouvelles mentions dans les ports et les régions environnantes. Sept taxons cryptogéniques (taxa qui pourrait être soit indigène ou non) ont été identifiés. Il a été constaté que la région étudiée devrait être considérée comme une source potentielle d'espèces non indigènes pour les ports d'autres régions, étant donné que les espèces indigènes (n = 8) sont connues pour être à leur tour des espèces non indigènes ou cryptogéniques ailleurs dans le monde.

Le chapitre 2 recourt à la modélisation de l'habitat pour prédire les distributions spatiales potentielles d'espèces envahissantes à haut risque compte tenu des facteurs abiotiques pour les conditions environnementales actuelles et prédites dans le cadre d'un scénario de changement climatique pour le milieu du siècle. Ce chapitre montre que des régions comme la baie d'Hudson et la mer de Beaufort fournissent déjà un habitat approprié dans les conditions environnementales actuelles pour trois des huit espèces modélisées : *Littorina littorea*, *Mya arenaria* et *Paralithodes camtschaticus*. En projetant la modélisation de l'habitat dans un scénario de réchauffement global, la pertinence de l'habitat augmente pour ces trois espèces. La modélisation des cinq autres espèces (*Apmhibalanus improvisus*, *Botrylloides violaceus*, *Carcinus maenas*, *Caprella mutica* et *Membranipora membranacea*) aboutit à la définition de nouveaux habitats adéquats dans la région de l'Arctique canadien.

Le chapitre 3 présente une évaluation des risques écologiques liés aux trois espèces pour qui, selon le chapitre 2, l'habitat est approprié dans les conditions environnementales actuelles. La pertinence de l'habitat, interprétée comme la probabilité de survie à l'établissement, a été mise en corrélation avec la probabilité de l'arrivée par le déchargement des eaux de ballast comme voie potentielle d'introduction. Tous ces facteurs, qui représentent la probabilité d'introduction, ont ensuite été combinés avec les conséquences potentielles que les espèces peuvent engendrer dans l'environnement selon la sensibilité de l'habitat. Les résultats de ces corrélations montrent que la région a probablement été exposée à l'arrivée de ces espèces et que le risque peut présenter différents schémas temporels et spatiaux. Un autre constat important qui découle de l'étude est que des événements de déballastage des navires domestiques posent en général un risque relativement plus élevé que le déballastage des navires internationaux, ce qui expose les ports de Deception Bay et de Churchill au risque relatif le plus élevé, en particulier pour les espèces *L. littorea* et *M. arenaria*.

Dans son ensemble, la thèse est une référence pour les suivis futurs et pour le développement de méthodes de détection rapide de nouvelles espèces dans la région de

l'Arctique canadien. De plus, elle fournit des connaissances qui pourraient être utilisées dans les prises de décisions à venir. L'étude souligne l'importance des efforts à faire pour échantillonner de façon adéquate les organismes benthiques dans les habitats côtiers de l'Arctique dans le but d'améliorer les données de base pour la comparaison et de permettre, à long terme, le suivi de changements potentiels sur les communautés. L'utilisation de la modélisation de l'habitat et l'évaluation du risque écologique aideront à la compréhension des menaces potentielles de l'arrivée, de la survie et de l'établissement d'espèces indésirables en raison du changement climatique et du trafic maritime à l'échelle de l'Arctique canadien. La thèse dans sa globalité préconise une approche de l'identification des régions et des espèces à haut risque afin de déployer des efforts de recherche plus ciblés en réponse au changement climatique.

Mots clés : Arctique canadien, benthos, base de référence, espèces non indigènes, espèces aquatiques envahissantes, introductions par navires, habitat propice, risque, réchauffement climatique

ABSTRACT

Climate change is leading to variations in environmental conditions, especially in temperature and ice cover in high latitude regions such as the Canadian Arctic. Predictive models and risk assessment represent key tools for understanding current and projected changes associated with the impacts on coastal regions. It is important to predict how the introduction of new species will interact with drivers such as climate change, shipping activity and increasing resource exploitation, as these can have a high economic and ecologic cost. Therefore, it is important to evaluate the current and future risks associated with new introduced species in a region like the Canadian Arctic. The main aim of this thesis is to characterize the native and non-native biodiversity of benthic invertebrates in ports of the Canadian Arctic where the risk for introduction is the highest; and to evaluate the overall risk for potential future aquatic invasive species in a scenario of increased global warming and shipping activity.

Chapter 1 includes the collection, compilation and comparison of contemporary and historical coastal biodiversity information. This chapter contributes to increasing the baseline information on the presence and distribution of benthic taxa in the main ports along the Arctic coastline. Due to the increased survey effort in the region, a total of 236 species and genus were identified, of which 7 to 15% were considered new records within the ports and surrounding regions. Seven cryptogenic taxa (taxa that could be either native or non-native) were identified. Interestingly, the region surveyed was also found to be a potential source of non-indigenous species to ports in other regions given that some native species (n=8) are known to be established non-indigenous species or cryptogenic elsewhere in the world.

Chapter 2 uses habitat modelling to predict spatial distributions for potential invasive species considering abiotic factors for current and projected environmental conditions under a climate change scenario by mid-century. This chapter shows that regions such as the Hudson Bay and Beaufort Sea already provide suitable habitats under current

environmental conditions for three out of eight species modelled: *Littorina littorea*, *Mya arenaria* and *Paralithodes camtschaticus*. When projecting the habitat modelling into a future scenario of global warming, there was an increase of habitat suitability for these three species, and the other five modelled species (*Apmhibalanus improvisus*, *Botrylloides violaceus*, *Carcinus maenas*, *Caprella mutica* and *Membranipora membranacea*) also had suitable habitats in the Canadian Arctic region.

Chapter 3 presents a relative ecological risk assessment for the three species that were found in Chapter 2 to have habitat suitability under current environmental conditions. The habitat suitability is interpreted as the likelihood of survival-establishment, and was combined with the likelihood of arrival through ballast water discharge as potential pathway of introduction. These factors represent the likelihood of introduction, which is then combined with the consequence of occurrence (potential impact that the species can have in the environment together with the habitat sensitivity). Results from this chapter shows that the region most likely has been exposed to the arrival of these species, and that the overall risk based on vessel specific averages can show different temporal and spatial patterns. Another important finding of this chapter is that, in general, domestic discharge events posed higher relative overall risk than international discharges, making the ports of Deception Bay and Churchill the ones with the highest relative risk, especially for the species *L. littorea* and *M. arenaria*.

Overall, this thesis provides a benchmark for future monitoring and aids in the development of methods for rapid detection of new species in the area, as well as providing information that can be used in decision making in the future. The study highlights the importance of making efforts to adequately sample benthic organisms in tidal and subtidal coastal Arctic habitats in order to improve baseline information, and allow for future tracking of potential changes in communities over time. Furthermore, the utilization of habitat models and ecological risk assessment will help in understanding potential threats of arrival, survival and establishment of future unwanted species as a result of climate change and shipping at the Canadian Arctic spatial scale. The ensemble of this thesis

provides an approach in the identification of high-risk regions and species to allow for more focused research and monitoring efforts in response to climate change.

Keywords: Canadian Arctic, benthos, baseline, non-indigenous species, aquatic invasive species, ship-mediated introductions, habitat suitability, risk, global warming.

TABLE DES MATIÈRES

LISTE DES TABLEAUX

LISTE DES FIGURES

LISTE DES ABRÉVIATIONS, DES SIGLES ET DES ACRONYMES

AIS	Aquatic Invasive Species
AOR	Arctic Outside Region
AUC	Area Under the Curve
BWE	Ballast Water Exchange
CA	Other Canadian Arctic regions
CCD	Circumpolar-Circumboreal Distribution
Ch	Churchill
Chest	Chesterfield
Cr	Cryptogenic
CR	Clyde River
DB	Deception Bay
EAA	European/Asian Arctic
HS	Habitat Suitability
Iq	Iqaluit
ISE	Increased Survey Effort
Kuuj	Kuujjuaraapik
MOE	Mid-Ocean Exchange
MT	Metric Tons
NIS	Non-indigenous species

OT	Other Temperate regions
PI	Pond Inlet
RB	Resolute Bay
RI	Rankin Inlet
SDM	Species Distribution Modelling
TNA	Temperate North America
Tuk	Tuktoyaktuk
WD	Wider Distribution including Arctic region
WG	West Greenland

INTRODUCTION GÉNÉRALE

THE CANADIAN ARCTIC: GLOBAL WARMING, SHIPPING ACTIVITY AND RESOURCE EXPLOITATION

The Arctic marine ecosystem and its relation with global warming

The entire globe is experiencing shifts due to climate change. In July 2015, the globally-averaged sea surface temperature was the highest for any month in the last 135 years; it was also the warmest month ever recorded on land (NOAA, 2015). Shifts in temperature have generally been higher in the ocean than on land (Burrows *et al.*, 2011). High latitude regions are highly sensitive to climate change, which may alter their temperature regimes, ocean currents, sea level and other key physical processes. The Arctic Ocean in particular is experiencing major changes due to global warming. The highest temperatures ever recorded since the onset of instrumental measurements were observed over the past decade, and the evidence suggests that recent Arctic summer temperatures were higher than during any time in the past 2000 years (Walsh *et al.*, 2011). Furthermore, during the last three years, the Arctic sea ice conditions have broken two records. As seen in Figure 1, 2012 was the record lowest sea ice extension during a summer season, and 2015 was the record lowest maximum ice extent during a winter season (NSIDC, 2015).

Different global models are used to simulate the effect of climate changes on Arctic sea ice. In 2001, the IPCC predicted that the Arctic may warm approximately 3-4°C or more than twice the global average under realistic greenhouse warming scenarios. Then, they predicted in 2007 that mean reductions of annually averaged sea ice area in the Arctic would attain 31% by 2080-2100 (IPCC, 2007). Other authors state that a complete disappearance of summer sea ice could be possible by 2037-2040 (Holland *et al.*, 2006; Wang & Overland, 2009; Hoegh-Guldberg & Bruno, 2010). Nevertheless, when comparing the models to the real data, it can be seen that changes in sea ice are happening faster than models have projected (Meier *et al.*, 2014).

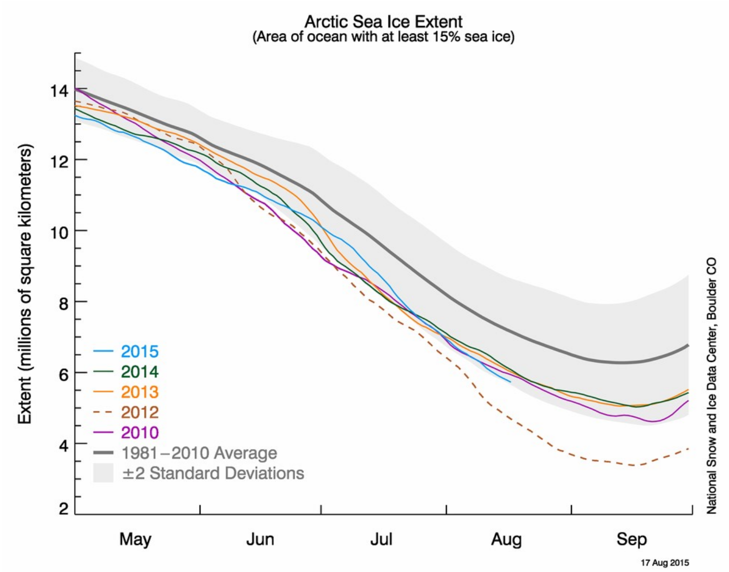


Figure 1: Arctic sea ice extent of the last five years (colour lines) and the average 1981-2010 in dark grey. The grey area around the average shows the two standard deviation range of data. The brown dashed line denotes the record of lowest sea ice extension (summer 2012) and the blue line denotes the record of lowest maximum sea ice extension (winter 2015). Image taken from the National Snow and Ice Data Center. Accessed on August 31st 2015.

The above mentioned changes can lead to profound variations in species dispersal and survival (IPCC, 2001; Hellmann *et al.*, 2008; Cheung *et al.*, 2009; Ruiz & Hewitt, 2009). Current knowledge on the impact of climate change on marine life is lacking compared to that available for terrestrial systems (Richardson & Poloczanska, 2008). According to Wassmann *et al.* (2011), only 51 reports documented changes in Arctic marine biota in response of climate change. Most of the responses involved northward shifts, decline in abundance and reproductive output, regime shifts, growth, behavior and phenology (Wassmann *et al.*, 2011). Given that the Arctic Ocean comprises 5% of the earth surface and 35% of the world coastline (Wassmann, 2015), it is obvious that all the changes and impacts observed in this region are globally significant.

Shipping and resource development in the Arctic

Shipping activities in the Canadian Arctic are extensive, but currently mainly consist of community re-supply, bulk shipments of raw materials and supplies, exploration activity for resource development operations, and tourism (Arctic-Council, 2009). Imports of goods are required for both industry and human settlements. Exports are mainly concentrated on the petroleum, fisheries and mining industries. Canada has one of the three major shares of the exports from the Arctic regions (Glomsrød & Aslaksen, 2006). Higher demands for goods and an increased accessibility to Arctic resources have resulted in a substantial increase in the number of shipping transits in the region (e.g. an increase of 70% of transits in only one year) (Gavrilchuk & Lesage, 2014).

Resource development in the Canadian Arctic dominates the rural economy of the north. Oil, gas, and other types of mining, particularly diamonds, have stimulated industrial development by Canadian and foreign multinational firms in remote areas with extreme climates. Mining, oil and gas account approximately for 36.4% of total economic activity in this region (Glomsrød & Aslaksen, 2006). Resource development continues to increase at a rapid pace (Haley *et al.*, 2011), and is expected to be accompanied by an increased export of resources mainly through shipping which is the only feasible means of transporting large volumes of cargo from many of these remote locations. According to Gavrilchuk and Lesage (2014), it is expected that more than 25 new development projects with a marine component will be operational in Canada's North by 2020. This will represent an approximate number of 433 shipments per year. The region is therefore expected to experience an unprecedented increase in industrial development over the next decade (Gavrilchuk & Lesage, 2014).

International and coastal domestic ports and the associated shipping traffic can act as a potential vector for species transfer via hull fouling or ballast water discharge. In fact, it has been described as the main vector for the introduction of new species globally (Molnar *et al.*, 2008). Ninety percent of the world trade is conducted by the ocean shipping network, which provides one of the most important modes of transportation (Kaluza *et al.*, 2010).

Canada established ballast water management regulations in 2000 to prevent aquatic non-indigenous species introductions: all international vessels entering and operating in Canadian waters that are at least 50 m in length with a minimum ballast capacity of 8 m^3 are required to undertake mid-ocean exchange (MOE) or ballast water exchange at sea (Transport Canada, 2007). Ballast water exchange is a process in which a ship exchanges ballast water of coastal origin with open-ocean saltwater (Chan *et al.*, 2012). The requirement for MOE is based on the theory that any open-ocean taxa present in exchanged ballast are less likely to succeed in coastal or freshwater environments because they are less adapted, diverse and abundant than coastal communities thus reducing the risk of successful invasion in coastal waters' (Levings *et al.*, 2004; Simard & Hardy, 2004). Domestic ships, however, can directly transport ballast water from Canadian temperate waters to Canadian Arctic waters without any form of management since Canada does not currently regulate discharges of domestic ballast water (Chan *et al.*, 2012). Given that the Arctic receives a considerable amount of international and domestic traffic, this region is particularly vulnerable to potential introductions of established aquatic invasive species, non-indigenous species and native species from temperate waters.

NON-INDIGENOUS SPECIES

What is a non-indigenous species?

One of the first things to consider when talking about non-indigenous species is that the invasion process includes consecutive stages, that it should be understood as a biogeographical rather than a taxonomic phenomenon (every species has its native range) and that invasion stages should be related to individual populations and not entire species (Colautti & MacIsaac, 2004). The terminology used to characterize non-indigenous species is extensive, and different concepts and uses of the terms can be found in the literature. Some commonly used terms include *alien*, *exotics*, *invaders*, *non-native species*, *introduced species*, *immigrants*, *translocated species*, *naturalized species*, *colonists*, *harmful species*, *adventives*, *neophytes*, *weeds*, *imports*, *nuisance* and *invasive species*, among many others.

The usage and particular meaning of the terms can vary among taxonomic groups and geographic regions (Ruiz & Carlton, 2003), and even in a scientific context, there is generally no agreement in what is meant by invasiveness (Boonman-Berson & Turnhout, 2013); hence it is crucial to define the terminology when talking about invasions. This lack of definition has plagued scientific literature for a long time, ever since the classical book of Elton (1958) on ecology of plants and animals, in which the term *invasive* is not even defined. In addition, the concepts and perceptions of non-indigenous species will be different according to who is defining it since there are different points of view from science, policy, conservation management or society (Boonman-Berson & Turnhout, 2013). Therefore, it is important to state and define at the very beginning of this thesis the terminology that will be used.

Two expressions will be utilized throughout this text: 1) non-indigenous species (NIS) to refer to species that have moved outside their normal geographic range due to human actions regardless of their eventual impact on native ecosystems (definition taken from Lockwood *et al*., 2007), and 2) aquatic invasive species (AIS) to refer to species introduced beyond their native range that have known adverse consequences for economic, environmental or human welfare (Colautti *et al.*, 2006b).

NIS characteristics and invasion process

There are biologically identifiable steps along the path to becoming an invader. Passing each stage requires overcoming several ecological barriers. All NIS originally began as individuals that were picked up from their native range, transported to a new area, and released into the wild ("Transport" in Figure 2). These individuals must then establish a self-sustaining population within their new non-native range, or else the population becomes extinct ("Establishment" in Figure 2). An established non-indigenous population may then grow in abundance and expand its geographic range, or it may remain at low abundance and locally distributed ("Spread" in Figure 2). Typically, ecological and economic harm will only occur when a non-native population becomes widespread and abundant, and thus earns the "invasive" title ("Invasion" in Figure 2) (Lockwood *et al.*, 2007). Nevertheless, it is important to add that impacts can be caused at any of the particular stages and that it is highly influenced by human perception. The magnitude of damage costs will depend on the probabilities of passing each of the invasion stages and on the impacts on different ecosystem services (Marbuah *et al.*, 2014).

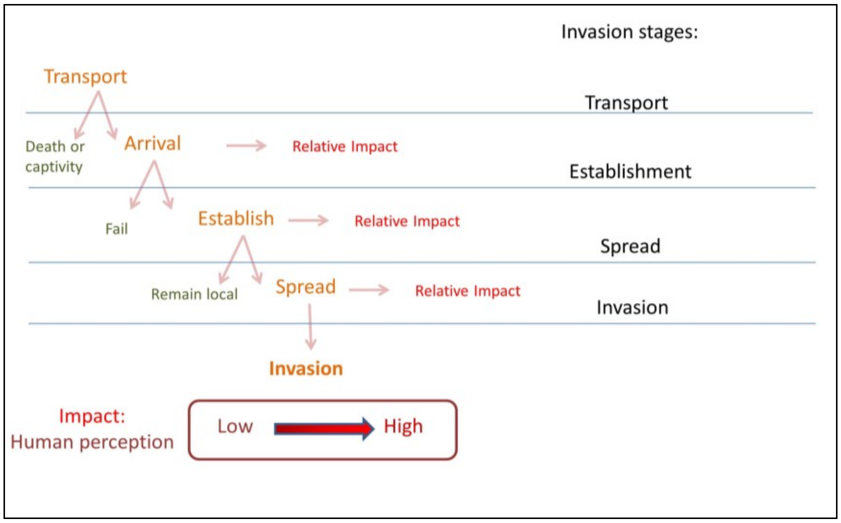


Figure 2: Invasion process model showing the discrete stages an invasive species passes through as well as alternative outcomes at each stage. Depending on the species and the effect they can cause, a relative impact can be given to each stage (taken and modified from Lockwood *et al.*, 2007).

The role of propagule pressure (number of individual arrivals and number of introduction attempts) and colonization pressure (number of exotic species introduced into a single location, some of which may succeed in establishing and some of which will not) is very important in determining the success of NIS establishment, although it is not always taken into account in studies on biological invasions (Ruiz *et al.*, 2000; Colautti *et al.*, 2006a). Propagule pressure is not easily measured directly, except with intentional species introductions, but can be indirectly related to some measures of the intensity of unintentional introductions (e.g., number of ships, estimated discharge ballast water) (Occhipinti-Ambrogi, 2007). The characteristics of the receiving community are also important in determining the success of NIS invasion. For example, success of NIS decreases with increasing resident species richness (Stachowicz *et al.*, 2002a) and loss of biodiversity can lead to degradation of local resistance against invasion (Kennedy *et al.*, 2002). Thus, a more diverse environment should result in lower total resource availability, decreasing the success of new species (Elton, 1958; MacArthur, 1970).

What is the harm of invasive species?

The introduction of a new species can cause ecological and socio-economic impacts on: biodiversity (e.g., reduction in species richness), habitats (e.g., habitat loss), biotic interactions (e.g., competition for resources or space), genetic (e.g., alteration to gene pools through hybridization), tourism (e.g., reduction on tourism activities), fishing (e.g., reduction in commercial species abundance), aquaculture (e.g., reduction in quality of the products), vessels-moorings (e.g., increased cost in maintenance as a result of fouling organisms), aesthetics-diving (e.g., reduction in the quality of aesthetic activities), etc. (Hewitt *et al.*, 2006). The ecological impacts can be also observed at different biological levels of organization: genetic, individual, population, community, ecosystem, regional and global, keeping in mind that what affects one level of organization will often affect other levels (Lockwood *et al.*, 2007). Moreover, the impact that a new species can have in an ecosystem can vary according to the perception (e.g., social, scientific, political, etc.).

It has been estimated that at any moment in time, over 7000 species might be moving around in ballast tanks in ships on the world's oceans (Carlton 2008 as cited in Rilov and Crooks, 2008). But what is the proportion of invasive species and what are the costs incurred by an invasion? North American waters are considered to have established populations of 450 marine and estuarine NIS (Ruiz *et al.*, 2015). In Canada, it has been calculated that at least 1442 different species have invaded forests, agricultural and aquatic ecosystems (MacIsaac *et al.*, 2002). In a freshwater ecosystem like the Great Lakes alone, it has been estimated that a new introduced species is discovered every 28 weeks (Ricciardi, 2006). An important consideration has to be made with analyses discussing the total number of introduced species in general: only 20-30% produce negative economic consequences (Pimentel *et al.*, 2001). Other studies state that we know the ecological and economic impacts of approximately 10% of the invasive species in a certain region (Vilà *et* *al.*, 2009). The costs of damages due to invasive species in Canada have been estimated to be close to $7.5 billion Canadian dollars (CDN) per year (Dawson, 2002). These damages, translated to costs in fisheries, agriculture and forestry, are around $187 million CDN per year for only ten of the most important NIS (Colautti *et al.*, 2006b). A recent study with a wider geographic coverage, calculated that the cost of invasive species vary from less than $1 million USD per year to even higher costs like 12% of gross domestic product for affected countries (Marbuah *et al.*, 2014).

Why study non-indigenous species in the Arctic?

Ever since 1924 the problem of harmful species has been recognized in international conventions (García-de-Lomas & Vilà, 2015). Over the past century, non-indigenous species have become a serious threat to biodiversity (Cohen & Carlton, 1998) with ecological, economic, health and environmental impacts. Intertidal and subtidal biota in many regions have undergone rapid and profound changes caused by the arrival of NIS (Carlton, 1996b; Ruiz *et al.*, 1997). Given that Canada has the longest coastline in the world (its territorial sea covers 14.3% of the territorial sea of the world), which is mostly located in Arctic waters, and that the Arctic Ocean is the least sampled of the world´s oceans and lacking of marine ecological knowledge, it can be said that this region is at high risk (Arctic-Council, 2009; Archambault *et al.*, 2010; Wassmann, 2015).

From a global perspective, the least invaded realms are the Southern and Arctic Oceans (Molnar *et al.*, 2008). The Arctic has been perceived as an unlikely region for biological invasions for two main reasons: 1) shipping activity is relatively low in the North compared to temperate ports, thus resulting in a reduced propagule supply of non-indigenous species; and 2) the severe environmental conditions (long periods of ice cover and severe ice scour) in the Arctic are expected to reduce the probability of survival of NIS, thus conferring resistance to invasions (Ruiz & Hewitt, 2009). Nevertheless, the Arctic can be considered to be threatened by introduction of ship-mediated NIS. The past few decades have seen a rapid acceleration in the rate of establishment of introduced species in coastal waters (Ruiz *et al.*, 2000; Ruiz *et al.*, 2015). The Arctic Marine Shipping Assessment (Arctic-Council, 2009) highlights the need for baseline surveys of aquatic species in ports of the Arctic region to investigate the potential presence of introduced species and assess the risk for future introduction of potential invaders. Most introduced marine species are benthic (Streftaris *et al.*, 2005), making these organisms a good study model and making it interesting to predict those species that could potentially be introduced in the Canadian Arctic. The general agreement is that the physical and biological disturbance levels due to climate change in Arctic waters will have an important impact on the structure and functioning of different systems, including the benthic one (Piepenburg, 2005).

THE CANADIAN ARCTIC AND NON-INDIGENOUS SPECIES

Global warming in the Arctic and species distribution

Climate change and invasive species are two of the most important threats to marine ecosystems since they can affect the structure and function of native communities (Stachowicz *et al.*, 2002b; Occhipinti-Ambrogi, 2007). Furthermore, invasive species may be favoured by warmer temperatures (Stachowicz *et al.*, 2002a; Occhipinti-Ambrogi, 2007; Sorte *et al.*, 2010; Cockrell & Sorte, 2013). According to Walther *et al.* (2002) and Sorte *et al.* (2010), based on theoretical and conceptual aspects and evidence for observed changes in biological invasions arising from recent research, climatic change is known to affect biotic components. These include changes in ecological communities and increased dominance of introduced species in competitive interactions and community development that cause shifts in community composition. It can also impact on differences in growth rates, patterns of mortality, timing, duration and magnitude of reproductive output for native species (Occhipinti-Ambrogi, 2007; Sorte *et al.*, 2010). These shifts to dominance by NIS may accelerate the homogenization of the global biota. Climate change can have a disproportionately negative impact on native species, and based on the temperature tolerance, survival and growth results, as ocean temperatures increase, native species will decrease in abundance, whereas introduced species are likely to increase in this system

(Sorte *et al.*, 2010). Aquatic communities are expected to present shifts in their distributions with southern species expanding their ranges to more northern locations (Cheung *et al.*, 2009; Cheung *et al.*, 2011). Under these conditions, invasive species are likely to have a competitive advantage, since they usually have larger latitudinal ranges than the native cold-water adapted species, possess the ability to tolerate a broader range of environmental conditions and can develop the potential for greater success at increased temperatures (Hoegh-Guldberg & Bruno, 2010; Sorte *et al.*, 2010). These processes are expected to create northward shifts and a borealisation of the Arctic Ocean. Specific predictions of where these changes will occur and which taxa are more likely to extend their ranges are however lacking (Wassmann, 2015).

Multiple interactions: shipping, global warming and NIS

The warming climate in high latitude regions is expected to result in increased accessibility and a longer shipping season (Arctic-Council, 2009). Global warming is likely to cause the recession of summer Arctic ice cover opening seasonal trading routes through the North-West Passage and the northern sea route (north of the North American and the Eurasian continents, respectively) as seen in Figure 3 (Smith & Stephenson, 2013; Miller & Ruiz, 2014). Increased connectivity between the North Pacific and Atlantic oceans will provide greater opportunities for transarctic movement of cold-water species, representing a vector for the transfer of NIS in ballast water or on hulls to new areas where the environmental conditions resemble those in their native waters. According to Smith and Stephenson (2013), the probability of open-water vessels crossing an ice free Northwest Passage will increase from its current 17-27%, to nearly the double (53-60%) by mid-century. In 2012, a record of 30 different kinds of vessels transited through the Northwest Passage, and in 2013, for the first time ever, a commercial vessel transited the Passage (Environment and Natural Resources, Northwest Territories 2015). More surprising still is the fact that people outside the shipping and industry business are also seeing new opportunities: for example, there is an extreme yacht race that is being organized for the summer 2017 to cross the Northwest Passage (Washington Post 2015).

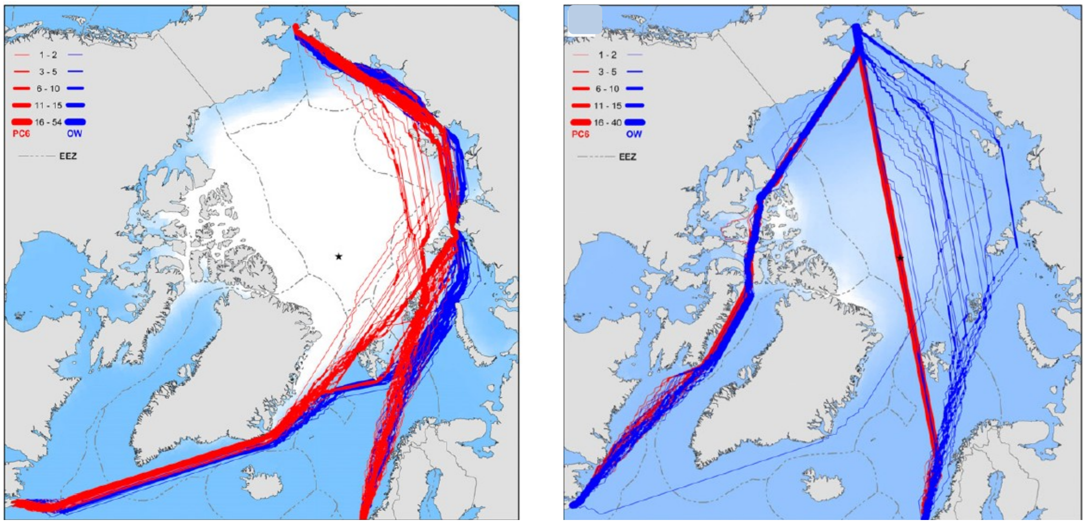


Figure 3: Optimal September navigation routes to cross the Canadian Arctic: a) historical baseline conditions (1975-2005), b) hypothetical ships seeking to cross the Arctic Ocean during 2040-2059 as driven by projection of sea ice concentration and thickness assuming RCPs 8.5 (high radiative forcing). Red lines indicate fastest available tans-Arctic routes for Polar Class ships; blue lines indicate fastest available transits for common open-water vessels. Taken from Smith and Stephenson (2013).

Reported NIS cases in the Arctic

A variety of recent introductions in high-latitude areas have been documented: the snow crab *Chionoecetes opilio* in the Barents Sea (Alvsvåg *et al.*, 2009); the Japanese skeleton shrimp *Caprella mutica*, the ascidian *Molgula citrina* together with 24 different species of plants and animals in marine related ecosystems in Alaska (Hines *et al.*, 2000a; Ashton *et al.*, 2008a; Lambert *et al.*, 2010); the Atlantic rock crab *Cancer irroratus* and the sea squirt *Ciona intestinalis* in Iceland (Svavarsson & Dungal, 2008; Gíslason *et al.*, 2014); the red algae *Dumontia contorta* in Hudson Bay (Mathieson *et al.*, 2010), as well as new polychaete species, such as *Aricidea hartmani* in Canada Basin, that have been discovered for the first time but whose origin is uncertain (MacDonald *et al.*, 2010). According to Ruiz and Hewitt (2009), there has been only one non-native benthic invertebrate marine species known to have an established population in the Arctic through intentional human introduction: the Alaskan king crab *Paralithodes camtschaticus*. It has been intentionally introduced in Norwegian and Russian waters (Jørgensen & Nilssen, 2011). Although there have been no reported ship-mediated invasive species in Arctic Canadian waters to date, few systematic surveys have been conducted in this region (particularly for invertebrates) making it problematic to determine if newly reported species are native or introduced. Although species might not be establishing, some might already have arrived in the region. For example, recently several non-indigenous barnacle species were found to have been transported alive in ships' hulls into Canadian Arctic ports (Chan *et al.*, 2015) and diverse crustaceans have been found transiting through ballast water tanks in regions of the European Arctic (Ware, 2014). On the other hand, early detection methods such as metabarcoding have detected sequences of species previously unreported for Canadian Arctic ports, such as the soft shell clam *Mya arenaria* and the mussel *Mytilus galloprovincialis*, together with seven different species of copepods (Brown et al unpublished). This could indicate that these species are arriving in Canadian Arctic ports, but that information on the establishment of populations and the observation of individuals during sampling is still missing.

Models projecting the distribution of species suggest that high-latitude shorelines are currently vulnerable to invasion by non-native species occurring at lower latitudes (de Rivera *et al.*, 2011). It has been shown that climate change has the ability to directly enhance the invasion success for marine tunicates, and the spread of these invasive organisms to the Arctic could present a significant risk to other levels in the trophic web such as benthic-feeding marine mammals, which are already at risk (Stachowicz *et al.*, 2002b). Furthermore, if shipping and resource development increase as expected with a warming climate, propagule pressure will also increase and the Arctic will be more vulnerable to future invasions (Chan *et al.*, 2012).

Conservation and management

As Ruiz and Hewitt (2009) explain, as there are few confirmed invasions in polar systems to date, there is now an opportunity to implement management actions and policy that would greatly limit invasions and their unwanted impacts. We lack robust information on the early stages of the introduction process, whether successful or not, even though they may provide essential information on the vectors transporting the species as well as the invasion process itself (Chang *et al.*, 2011). The decline in existing populations of native species can be overlooked and go unnoticed in some cases, due to lack of previous data or insufficient taxonomic information.

The consequences of climate change for invasions at high latitudes deserve serious attention from a conservation and management perspective. While global shifts in temperature are underway and serve to increase chances of polar invasions, it appears that human responses to climate change will largely determine the number of invasions that occur. Although non-native species can arrive to polar ecosystems by natural dispersal (Barnes *et al.*, 2006), these regions are relatively isolated geographically, and the probability for human transport is far greater. Significant efforts should now focus on understanding and reducing the transfer of non-native species to the poles, aiming to avoid the high number and significant impacts of introductions experienced in temperate waters. Efforts to minimize invasion risk at lower latitudes have employed several approaches that are applicable and should be adopted in polar-regions. Among them, the prevention or reduction of species transport by human activities and rapid detection of invasions by non-native species (Ruiz & Hewitt, 2009) can be mentioned. In any case, we need to bear in mind that the presence of a new species does not automatically lead to successful establishment, but it is urgent to know the risks that NIS pose and to take preventive actions to limit their potential impacts.

GENERAL OBJECTIVES

This thesis is part of a national surveillance program, proposed by the Canadian Aquatic Invasive Species Network (CAISN), initiated to develop an information database on occurrence of aquatic invasive species and to aid in their rapid detection in key ports across the country.

The general objectives of this thesis are:

- to characterize existing native and non-native benthic invertebrates in coastal areas of the Canadian Arctic where the risk for introduction of NIS is the highest and
- to characterize and evaluate the overall risk for future aquatic invasive species incursions with changes related to global warming and shipping activity.

Figure 4 below summarizes the main factors influencing the risk of NIS together with the general objectives.

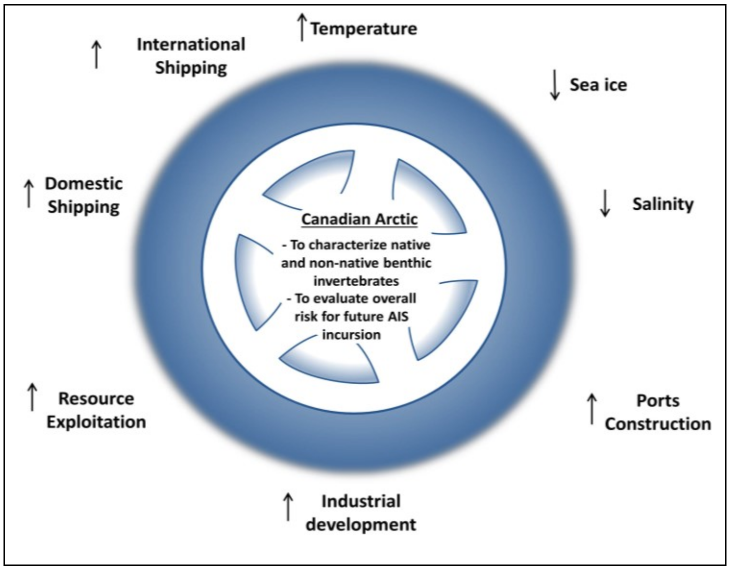


Figure 4: Representation of the general objectives and the main drivers that influence the risk of non-indigenous species in the Canadian Arctic region.

The general objectives are addressed in three chapters that are not only related to each other conceptually, but it also has a time component. This can be illustrated with the "*wheel of time*" (Figure 5), the conceptual model of this thesis, which circulates through different periods of time and through the various drivers (elements explained in the previous section) related to the introduction of new species.

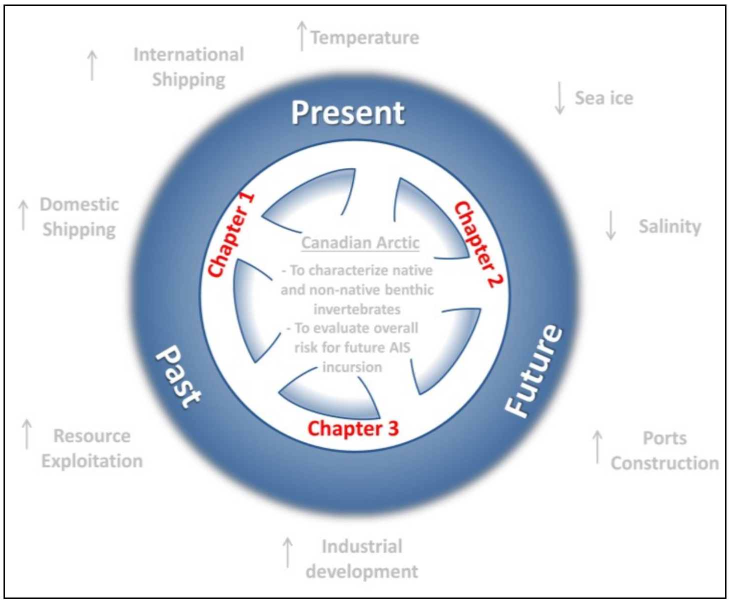


Figure 5: Conceptual model of thesis structure as a "*wheel of time*". It can be seen how the chapters are related to each other and how they are also related to a time component.

Specific objectives

Chapter 1: Establishing a baseline for early detection of non-indigenous species in ports of the Canadian Arctic

Chapter 1 involves the collection, compilation and comparison of contemporary and historical coastal benthic biodiversity information to address the following objectives:

a) to identify potential temporal changes in species composition and new species records by comparing existing benthic communities in intertidal and subtidal areas of Canadian Arctic ports where historical biodiversity information is available; and

b) to evaluate and determine the source (introduction, range expansion or increased survey effort) of new species records for the benthic coastal biodiversity in the Canadian Arctic (Section *a* in Figure *6*).

This chapter provides a comprehensive baseline of benthic biodiversity in ports of the Canadian Arctic. The hypotheses are related to the source of new reported species in the Canadian Arctic:

Hypothesis 1: Species with no previous records in the region of the studied ports but with previous records from neighboring areas and present in other parts of the Canadian Arctic can be explained by increased survey effort.

Hypothesis 2: Species with records in the European and Asian Arctic regions can be explained by increased survey effort if they do not have previous known introduction histories and if they show a pattern of circumpolar or cosmopolitan distribution.

Hypothesis 3: Species with records in Temperate North America (Atlantic side) can be explained by either range expansion or ship mediated introduction when matching with shipping connections.

Hypothesis 4: Species records from Temperate North America (Pacific side), Arctic and Subarctic Europe and Asia, and Temperate Europe and Asia can be explained by ship-mediated introduction when matching a known shipping connection.

As seen in Figure 6, this chapter relates present and past. The past, represented by the historical records and knowledge of the biodiversity in the region, is compared to the contemporary biodiversity to identify potentially new species occurring in the region surveyed.

Chapter 2: Projecting the present and future habitat suitability of aquatic invasive species in the Canadian Arctic

The objective of Chapter 2 is to predict the habitat suitability for a subset of potential high risk invaders connected to Canadian Arctic ports through shipping and to assess their likelihoods of establishment under both current conditions and under a future scenario of climate change. This approach allows the prediction of areas with higher invasion risk as a function of future global warming and increased shipping activity (Section *b* in Figure 6). The hypotheses of Chapter 2 are related to the differences in suitable habitat under different scenarios and the locations where the biggest changes are predicted:

Hypothesis 1: With future global warming, a greater number of temperate ship-mediated high risks AIS will encounter conditions suitable for establishing and occupying a wider range of habitats in the Canadian Arctic thus placing more ports of this region at higher risk.

Hypothesis 2: Hudson Complex has a higher habitat suitability compared to the other Canadian Arctic regions due to the fact that the region has more favorable conditions (relatively shallow, higher temperature, lower salinity when compared to other Canadian Arctic areas).

As seen in Figure 6, this Chapter focuses on present and future. The present is represented by the species' habitat suitability under current environmental conditions, while the future is represented by the projected changes under a global warming scenario and compared to the one modelled in the present.

Chapter 3: Ecological risk assessment of predicted marine invasions in the Canadian Arctic

Chapter 3 aims to spatially characterize the relative ecological risk of invasion for future AIS incursions across the Canadian Arctic ports (Section *c* in Figure 6). This chapter is directly related to Chapter 2, since the former provides the base for projections of suitable habitat of AIS in the Canadian Arctic region. Chapter 3 completes this assessment and addresses the following question: what is the ecological risk of invasion for the AIS for which suitable habitat is predicted in the Canadian Arctic? The hypotheses of this chapter are:

Hypothesis 1: When comparing domestic ballast water discharge to international ones, domestic ports receiving a higher amount of ballast water discharge on a vessel basis have a higher relative risk of introduction compared to international discharges.

Hypothesis 2: Species with a wider distribution (in their native and non-native ranges) have a higher risk of being introduced in Canadian Arctic waters either by international or domestic ballast water discharges.

As seen in Figure 6, this Chapter relates past and future. The past is represented by the recent past shipping records and the future by the assessment of potential risk of introduction of new AIS in the region.

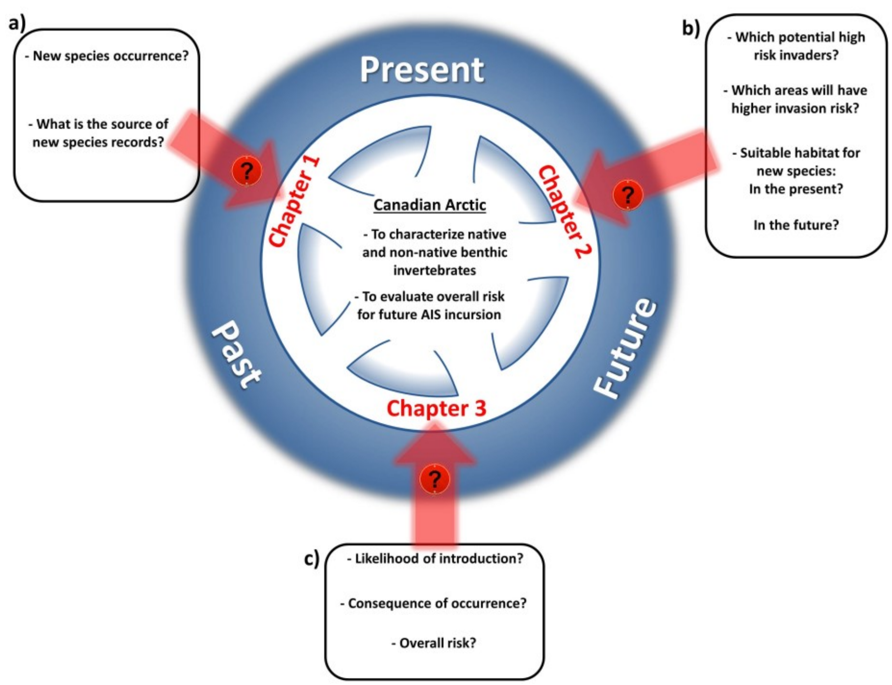


Figure 6: Conceptual model of thesis structure as a "*wheel of time*". It can be seen for each chapter which are the main questions that the thesis aims to answer.

CHAPITRE 1
ÉTABLIR UNE BASE DE RÉFÉRENCE POUR LA DÉTECTION ANTICIPÉE DES ESPÈCES NON INDIGÈNES DANS LES PORTS DE L'ARCTIQUE CANADIEN

RÉSUMÉ

La combinaison du réchauffement global, de l'exploitation des ressources et de l'augmentation de l'activité de navigation dans l'Arctique devrait accroître le risque d'introduction d'espèces exotiques dans les eaux arctiques dans un avenir proche. Nous fournissons ici pour la première fois une étude sur les invertébrés benthiques de façon à identifier les espèces non indigènes (NIS) des côtes de l'Arctique canadien, en incluant des données historiques, et à signaler la présence de nouvelles espèces. Les trois principaux ports exposés au plus haut risque d'introduction de NIS dans l'Arctique canadien ont été examinés : Churchill (Manitoba), Baie Déception (Québec) et Iqaluit (Nunavut). Un total de 236 genres et espèces ont été identifiés. Selon les informations contemporaines et historiques sur la composition et la distribution des espèces, 14,4 % des taxons identifiés peuvent être considérés comme de nouvelles introductions dans les régions portuaires étudiées et représentent 7,2 % en élargissant aux régions adjacentes. L'effort accru de recherche est l'explication la plus probable pour la majorité des nouveaux cas. Néanmoins, un petit nombre de détections (n = 7) sont des nouvelles mentions pour le Canada et ont été classées comme espèces cryptogéniques puisque nous ne pouvions pas les décrire avec confiance comme étant soit indigènes, soit introduites. Des recherches complémentaires sont nécessaires pour mieux comprendre le statut de ces nouveaux taxons. La présente étude fournit un point de référence pour la détection anticipée d'invertébrés benthiques dans la région. Les études de détections anticipées ainsi que leur suivi engendrent d'importants coûts et requièrent une main-d'œuvre considérable, mais ces travaux sont l'occasion d'identifier la biodiversité indigène et introduite, ce qui est crucial pour analyser

les changements qui ont lieu le long d'une des côtes les plus longues au monde : la côte de l'Arctique canadien.

ESTABLISHING A BASELINE FOR EARLY DETECTION OF NON-INDIGENOUS SPECIES IN PORTS OF THE CANADIAN ARCTIC

ABSTRACT

The combination of global warming, resource exploitation and the resulting increase in Arctic shipping activity are expected to increase the risk of exotic species introductions to Arctic waters in the near future. Here, we provide for the first time a benthic invertebrate survey for non-indigenous species (NIS) from the Canadian Arctic coasts, incorporating historical information to identify new records. The top three ports at highest risk for introduction of NIS of the Canadian Arctic were surveyed: Churchill (Manitoba), Deception Bay (Quebec) and Iqaluit (Nunavut). A total of 236 genera and species were identified. Based on cross referencing comparisons of contemporary and historical information on species composition and distributions, 14.4% of the taxa identified can be considered new records within the port regions surveyed and 7.2% within the more extended, adjacent surrounding regions. Increased survey effort is the most likely explanation for the majority of new occurrences, however, a small number of records (n=7) were new mentions for Canada and were categorized as cryptogenic since we could not confidently describe them as being either native or introduced. Further research is required to better understand the status of these new taxa. This study provides a benchmark for early detection for benthic invertebrates in the region. Significant costs and intensive labor are involved in monitoring and in early detection surveys, but they provide a great opportunity for identifying native and introduced biodiversity, crucial to analyzing the changes taking place along one of the longest coastlines in the world, the Canadian Arctic coast.

Key words: Arctic, biological invasions, benthos, spatial distribution, shipping activity, risk for introduction

This first publication was co-authored by me, Dr. Kimberly Howland and Dr. Philippe Archambault. It has been accepted in its final version and published by the editors of the journal *Aquatic Invasions* in 2014 as part of a special issue on Aquatic Invasive Species. As first author, I conducted field work, laboratory, data and statistical analysis and wrote the publication. Dr. Howland and Dr. Archambault designed the original idea of the study, the basis of the fieldwork and contributed to the analysis and writing. Dr. Howland participated as well in the fieldwork.

Parts and short versions of this publication were presented as oral and poster presentations at the following conferences: 1) Aquatic Invasive Species Network Annual General Meeting in Montreal (Canada) in May 2012; 2) Québec-Océan Symposium in Montreal (Canada) in November 2012; 3) International Congress on Aquatic Invasive Species in Niagara Falls (Canada) in April 2013; 4) Aquatic Invasive Species Network Annual General Meeting in Kananaskis (Canada) in May 2013; 5) Association of Polar Early Career Scientist in an online conference in April 2014; 6) Canadian Aquatic Invasive Species Network Annual General Meeting in Gatineau (Canada) in April 2014; 7) Coastal Zone Canada in Halifax (Canada) in June 2014.

Goldsmit, J., Howland, K.L., and Archambault, P. (2014) Establishing a baseline for early detection of non-indigenous species in ports of the Canadian Arctic. *Aquatic Invasions*, 9 (3): 327-342, doi: http://dx.doi.org/10.3391/ai.2014.9.3.08

INTRODUCTION

Changes in climate, hydrography, and ecology related to global warming are presently, and are expected to continue to be, more strongly expressed in the Arctic Ocean relative to other regions of the world (IPCC, 2001; Hoegh-Guldberg & Bruno, 2010). These changes are hypothesized to have an important impact on the structure and functioning of Arctic benthic systems (Piepenburg, 2005) but these systems are still understudied (Wassmann *et al.*, 2011). The combination of these modifications can be expected to facilitate introductions of non-indigenous species (Strayer, 2012). Coastal waters have been shown to be more susceptible to non-indigenous species (NIS) since intertidal and subtidal biota in many regions have undergone rapid and profound changes caused by the arrival of NIS (Carlton, 1996a; Ruiz *et al.*, 1997). Although most introductions have occurred in southerly latitudes where there is the greatest shipping activity, the combination of global warming, resource exploitation and the resulting increase in Arctic shipping activity are expected to increase the risk of exotic species introductions to Arctic waters in the near future (Niimi, 2004; Arctic-Council, 2009; Smith & Stephenson, 2013). Canada has the longest coastline in the world (its territorial sea covers 14.3% of the territorial sea of the world and its coastline is 16.2% of the world total), the majority of which is located in Arctic waters (Archambault *et al.*, 2010). Given the extent of coastline in the Canadian Arctic, it can be considered a region that is, and will continue to be, at high risk for future introductions of NIS.

Over the last two decades, high-latitude areas have shown a disproportionate increase in temperature, and their coasts are highly susceptible to a combination of climate change impacts in addition to sea-level rise (IPCC, 2007; Hoegh-Guldberg & Bruno, 2010). In summer 2012, the decline in the Arctic sea-ice was the lowest ever recorded (NSIDC, 2012). It is projected that there could be a further 31% mean reduction of annually averaged sea ice area in the Arctic by 2080-2100 (IPCC, 2007), and there are even more extreme projections like the complete disappearance of summer sea ice by 2037 (Hoegh-Guldberg & Bruno, 2010). These projected changes will result in warmer, less saline, ocean conditions, which together with increased shipping activity (Arctic-Council, 2009; Smith & Stephenson, 2013), are expected to favour the establishment of high risk ship-mediated invasive species. Canadian Arctic ports are connected to international and Canadian coastal domestic ports, resulting in potential for species transfers via hull fouling and/or ballast water discharge (Chan *et al.*, 2012). Research on the climate-driven reductions in Arctic sea ice predicts that, by 2040 to 2059, new shipping routes will become passable across the Arctic (many through the Canadian Arctic), linking the Atlantic and Pacific oceans (Smith & Stephenson, 2013). This will result in an increase in vessel traffic with implications for the ecosystems of this fragile area including an increased probability of introducing non-indigenous species due to greater propagule pressure. Increasing temperatures are also expected to result in shifts in aquatic communities with southern species expanding their ranges to more northern locations (Ruiz & Hewitt, 2009; Chust *et al.*, 2013; Valle *et al.*, 2014).

New species reported in the Arctic may be native to this region but not previously described, such as the polycheate *Streptospinigera niuqtuut* Olivier, San Martin and Archambault, 2013 (Olivier *et al.*, 2013). On the other hand, unrecognized introduced species could be assumed to be native to the region (Carlton & Geller, 1991; Petersen, 1999). Some species could be either native or non-native (classified as ‘cryptogenic’) due to the lack of baseline surveys and information on historical species ranges, as is the case for the Canadian Arctic coast (Carlton & Geller, 1991; Carlton, 1996b; Ruiz *et al.*, 1997). Underestimation of NIS is probably always high in a given region (Ruiz *et al.*, 1997; Bax *et al.*, 2001) for the above described reasons, but also because of the taxonomical challenges of studying and identifying small organisms and poorly known taxa (Bax *et al.*, 2001). The challenge becomes greater knowing that many species remain to be described. There are estimates that 91% of species in the ocean still await description (Mora *et al.*, 2011), and that between one-third and two-thirds of marine species may be undescribed (Appeltans *et al.*, 2012b). To date, there have been no reported ship-mediated NIS in Arctic Canadian waters; however, the Arctic Ocean is the least sampled of the world´s oceans (Arctic-Council, 2009), and few systematic surveys have been conducted in this region of the country (particularly for benthic invertebrates) making it problematic in determining if newly reported species are native or introduced. In particular, the systematics and biogeography of benthic coastal invertebrates in the region are poorly known and mostly underestimated (Archambault *et al.*, 2010). Regionally speaking, for the whole Arctic and sub-Arctic, a review of the literature revealed one north-eastern Asiatic crustacean, *Caprella mutica* Schurin, 1935, to be successfully established in Alaskan waters (Ashton *et al.*, 2008b) and the Alaskan king crab, *Paralithodes camtschaticus* (Tilesius, 1815), which has established non-indigenous populations in the Russian and Norwegian Arctic (Orlov & Ivanov, 1978; Jørgensen & Nilssen, 2011), causing substantial impacts on the invaded environments (Oug *et al.*, 2011). An additional 10 NIS have been found in waters of Alaska, but without specific invasion success information (Hines *et al.*, 2000b; Ruiz & Hewitt, 2009). Also, one introduced species of benthic alga, *Dumontia contorta* (S.G.Gmelin) Ruprecht, 1850, has been recorded in James Bay and Ellesmere-Baffin Island, Canada (Mathieson *et al.*, 2010). This alga is thought to have originated from Europe and was first observed in the Western North Atlantic at the beginning of the 20th century; the means of introduction to North America is unknown (Mathieson *et al.*, 2008). Another species of alga, *Spyridia filamentosa* (Wulfen) Harvey, 1833, also recently found in the James Bay area of Canada, is considered cryptogenic as it is unclear if it was introduced (e.g., by migrating bird species) or if it originated from relict populations that survived from the mid-hypsithermal period (ca. 7000 years ago) (Mathieson *et al.*, 2010). In the latest Arctic Biodiversity Assessment, Lassuy and Lewis (2013) provide a review of all terrestrial and aquatic species that have invaded the Arctic realm.

We lack robust information on the early stages of most introductions, whether successful or not, even though they may provide essential information on the vectors transporting the species as well as the invasion process in itself (Chang *et al.*, 2011). As explained previously, lack of baseline data or insufficient taxonomic information can result in unnoticed changes related to aquatic community composition and existing populations of native species. There is a need for baseline research in order to determine if a species is new to an area and to detect changes within the probable introduction pathways (i.e., early detection) (NISC, 2003). The shipping activity in a given region of study can result in the frequent release of propagules, and introduces the probability that at any given time some species are in the early stages of establishment, and may not be detected until several generations after they establish (Carlton, 2009). Locke and Hanson (2009) propose a framework for rapid response to non-indigenous species which includes a detection phase during which they recommend the development of ecological inventories to establish baseline information on native and NIS populations. It is extremely important to know what was previously present to be able to identify new arrivals. The Canadian Arctic coasts can be considered a poorly studied area particularly with respect to benthic invertebrate biodiversity (Archambault *et al.*, 2010; Piepenburg *et al.*, 2011) thus emphasizing the importance of sampling and monitoring high-risk locations such as ports.

In this context, the objectives of this study were: 1) to compare species lists generated from a biodiversity survey performed in 2011 and 2012 in high risk port areas of the Canadian Arctic with historical survey information to identify new species and to evaluate if new records are best explained by increased survey effort, range expansions, ship mediated introduction, or other mechanisms and 2) to establish a baseline of biodiversity of coastal benthic invertebrates for further monitoring and early detection of aquatic non-indigenous species. This baseline will aid in identifying and managing new introductions of species in the Arctic, a region which is experiencing rapid change.

MATERIALS AND METHODS

Characteristic of the ports sampled

Three major Canadian Arctic ports: Churchill, Deception Bay and Iqaluit, Canada (Figure 7), were sampled because of their level of shipping activities. These ports are considered to be at highest risk for the introduction of NIS based on a recent assessment of the number of vessel arrivals and ballast discharge for all vessel categories between years 2005–2008 (Chan *et al.*, 2012; Chan *et al.*, 2013).

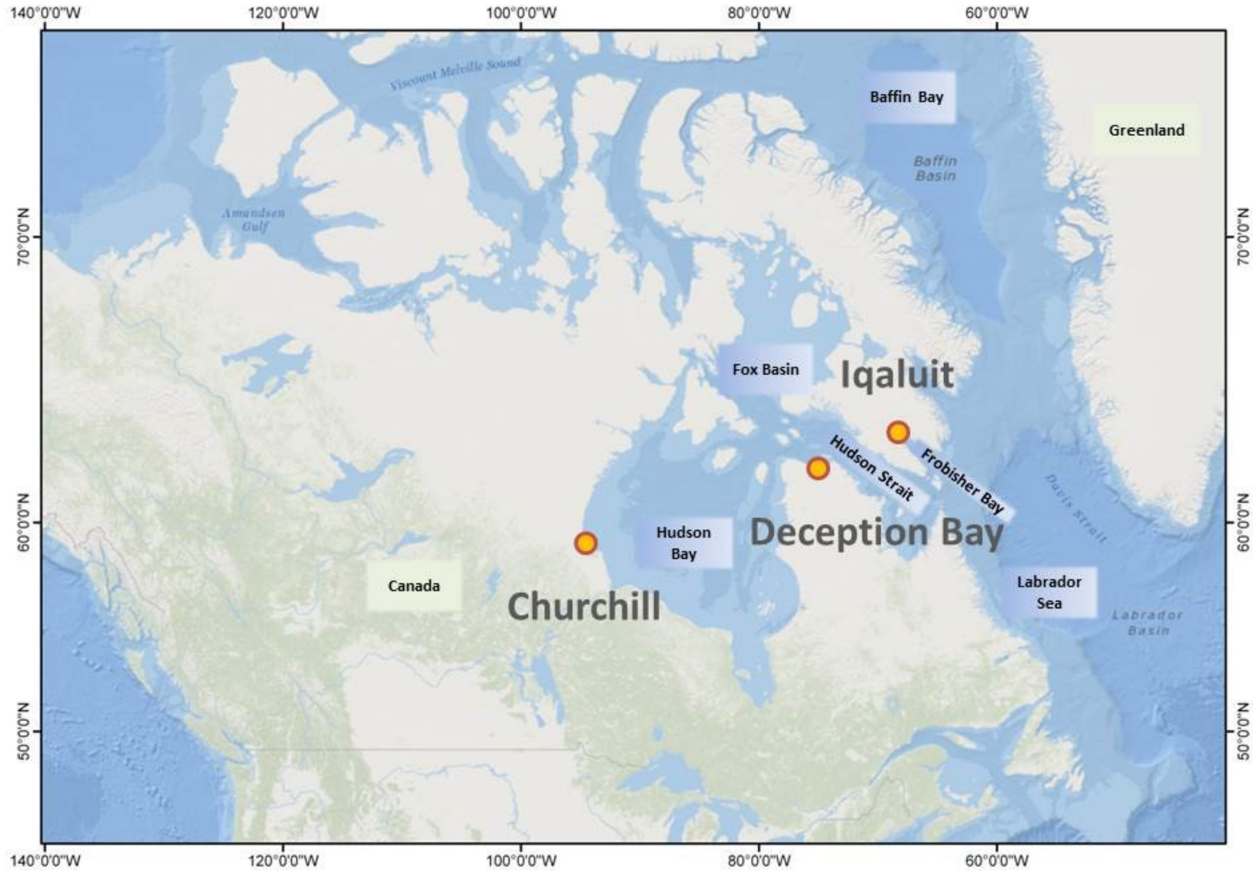


Figure 7: Map of the ports sampled: Churchill, Deception Bay and Iqaluit.

Churchill is located on the south western shores of Hudson Bay and is the major seaport in the region (Figure 7). Hudson Bay is connected to the Labrador Sea through Hudson Strait and is considered to be a large inland sea (surface area exceeds 1 million km^2) but is relatively shallow (an average depth of less than 150 m) and therefore warmer than many other regions of the Arctic (Saucier *et al.*, 2004; Séguin *et al.*, 2005). The Hudson Bay complex is comprised of sub-regions such as Hudson Strait, Foxe Basin and Hudson Bay, among others (Figure 7). Churchill's main shipping activities are related to its unique location that provides opportunities for international traffic, dominated mainly by the export of grain, followed by manufactured, mining, and forest products, as well as the import of ores, minerals, steel, building materials, fertilizer, and petroleum products for distribution in the heartland of Canada and the United States. Churchill is currently the port at highest relative invasion risk for the Canadian Arctic since it receives the highest number of vessels and volume of ballast discharge, and is environmentally similar to a large number of connected source ports with established high risk NIS (as compared to other ports in the Arctic) (Chan *et al.*, 2012). Mean values (± SE), between the years 2005–2008 of annual number of arrivals of international merchant vessels (17.75 ± 1.65) and the untreated annual volume of ballast water discharge (157,675 ± 19,409 m^3) in Churchill were the highest of all Canadian Arctic ports (Chan *et al.*, 2012).

Deception Bay is located in northern Quebec, and is part of the Hudson complex since it is surrounded by the waters of Hudson Strait (Figure 7). Its main activity involves shipping from a single-base metal operation that exports nickel concentrate to Quebec (Arctic-Council, 2009). A new mining development is scheduled to start exporting ore to Finland in 2013, which is expected to increase the shipping traffic in Deception Bay port. It is predicted that by 2014, a total of 2.9 Mt will be shipped annually out of this port (Gavrilchuk & Lesage, 2014). According to Chan *et al.* (2012), Deception Bay is in the top 3 ports receiving the greatest number of arrivals and releasing the greatest volumes of untreated ballast water for international and coastal domestic merchant vessels. Mean values (± SE), between the years 2005–2008 of the annual number of arrivals of international and coastal domestic merchant vessels in Deception Bay were 8.75 ± 4.15 and 9.50 ± 1.50, respectively (Chan *et al.*, 2012). The values for the volumes of untreated ballast water were 8,069 ± 4,020 m^3 for international merchant vessels and 60,144 ± 11,852 m^3 for coastal domestic merchant vessels (Chan *et al.*, 2012). This port was also found to have high environmental similarity with a large number of its source ports, thus increasing the probability of survival of NIS (Chan *et al.*, 2012).

Iqaluit is located in the Eastern Arctic, at higher latitude than the other ports studied and it is situated in the southern portion of Baffin Island on Frobisher Bay (Figure 7). It is the capital of Nunavut, the largest community in that province (more than 7,250 habitants) and the gateway to the Arctic from Eastern Canada. Tidal amplitude may reach as much as

13 meters, and sea ice in Frobisher Bay area consists almost entirely of annual ice which does not break up until the middle of July (Ellis & Wilce, 1961; Jacobs & Stenton, 1985). The annual volumes of dry goods and petroleum products being shipped to Iqaluit have been increasing dramatically and other potential marine activities and tourism have also increased since 1980 (Aarluk-Consulting *et al.*, 2005). Iqaluit's port is being used for different activities: dry cargo handling (government, commercial and private use), petroleum shipping, fisheries, tourist cruise ships, Canadian Coast Guard, military and research vessels, and small craft operators like hunters and fishermen (Aarluk-Consulting *et al.*, 2005). Iqaluit was found to have a high level of international and coastal domestic merchant vessel arrivals as well as international non-merchant vessel arrivals and is among the top ports in the Canadian Arctic for invasion risk via hull fouling (Chan *et al.*, 2012). Mean values (± SE), between the years 2005–2008 of the annual number of arrivals of international merchant vessels in Iqaluit were 12.00 ± 1.08, of coastal domestic merchant vessels were 15.00 ± 1.87, and of international non-merchant vessels were 9.25 ± 1.60 (Chan *et al.*, 2012).

Sampling strategies

Surveys for benthic samples were conducted during the summer in 2011 and 2012, using the following design: 5 zones per port x 4 elevations per zone (2 intertidal, 2 subtidal) x 4 random replicate samples per elevation. The port area and its surroundings, including both marine and estuarine habitats, were sampled. Different natural substrates were sampled in order to maximize coverage of coastal biodiversity based on shoreline characteristics that could be discerned from hydrographic charts and visual observations prior to sampling. The sampled elevations included two intertidal (high and low elevation) and two subtidal (shallow: 0–10 m, and deep: 10–20 m; at low tide). Random replicate samples were collected at each zone-elevation location using a 15 cm high x 10 cm diameter core and sieved to a minimum of 500 μm. The total number of samples collected at the port of Iqaluit (n= 46) was lower than in the ports of Churchill and Deception Bay (n= 80) due to variation in tidal conditions, weather, and time constraints that limited sampling opportunities at some locations (Table 1). All samples were preserved in 4% buffered formalin.

Table 1: Detail of core samples taken at each port according to zones and replicates.

Elevation	Iqaluit		Churchill		Deception Bay	
	Zones	Replicates	Zones	Replicates	Zones	Replicates
High intertidal	5	4	5	4	5	4
Low intertidal	Not available		5	4	5	4
Shallow subtidal	5	4	5	4	5	4
Deep subtidal	2	4	5	4	5	4
Total of core samples	48		80		80	

Samples were sorted and identified to the lowest taxonomic level possible, using updated literature and consulting with specialists, which included sending them samples for verification as necessary. All species names were standardized to the World Register of Marine Species (WoRMS) (Appeltans *et al.*, 2012a). The term 'taxa' refers to species and generic-level identifications unless otherwise noted.

Cross referencing and data analysis

The taxa identified were included in a cross-referencing protocol with the objective of detecting taxa that are out of their regular and described known range. This protocol included more than 40 references and was designed to allow for comparison of temporal changes in species presence through the compilation of a comprehensive historical database of benthic species from throughout the Canadian Arctic (See Appendix I). The references used included historical primary publications and the following global biodiversity databases: Ocean Biogeographic Information System (OBIS, 2013), Arctic Ocean Diversity (Sirenko *et al.*, 2010), Global Biodiversity Information Facility (GBIF, 2013) and Sea Life Base (Palomares & Pauly, 2013), together with the Smithsonian National Museum of Natural History databases (NMNH, 2012). Synonym names available in WoRMS (Appeltans *et al.*, 2012a) were also cross referenced with the same protocol when necessary. Consulting with specialists on the taxa was done, when possible, regarding taxonomic and distribution characteristics, especially for new records in the region of study.

Five categories were used to define the subregions of closest records for the species found in the ports surveyed: 1) ‘within region’: previous records in the exact area where the port is located, 2) ‘surrounding region’: no previous records for the exact region where the port is situated, but previous records from neighbouring and close areas, 3) ‘Arctic outside region’: species’ distribution known from elsewhere in the Canadian Arctic, but not specifically in the region of the port surveyed or its vicinity (surrounding region) and/or species records found in other neighbouring Arctic ecoregions according to the bioregionalization by Spalding *et al.* (2007), 4) ‘circumpolar/ circumboreal distribution’: species that have a wider Arctic distribution and have been found at several locations throughout the larger Arctic realm (Spalding *et al.*, 2007), but have not previously been found within the ports surveyed or their surrounding regions, 5) ‘wider distribution, including Arctic’: species or genus that show a wide and extended distribution, present in other realms as well as in the Arctic realm, but not previously found in the surveyed ports or their surrounding regions (Figure 8). This information was used to infer if the occurrence of new species was likely due to range expansions, improved survey effort, or possible introduction in a particular area. More detailed information from literature searches was obtained for taxa corresponding to all categories except for the ones ‘within region’ and ‘surrounding region’. Extensive lists of NIS available on the web and in research reports were consulted to identify if any were present in our species list.

The category of cryptogenic was given to taxa that were found to be new mentions for the whole Canadian Arctic and based on known distributional patterns, and NIS lists could not be confidently described as either native or introduced (Carlton, 1996b).

Unbiased nonparametric estimator of species richness, Chao 2, for replicated incidence data (Chao, 1984; Colwell & Coddington, 1994) was used to test adequacy of sampling effort in characterizing biodiversity in our study sites. It was calculated using PRIMER software (Clarke & Gorley, 2006). This method predicts the expected number of species which would be observed for an infinite number of samples by extrapolating, based on the number of rare species in the available data. PRIMER was also used to calculate resemblance matrices between ports with Bray-Curtis distances in order to see the similarities between ports for species composition.

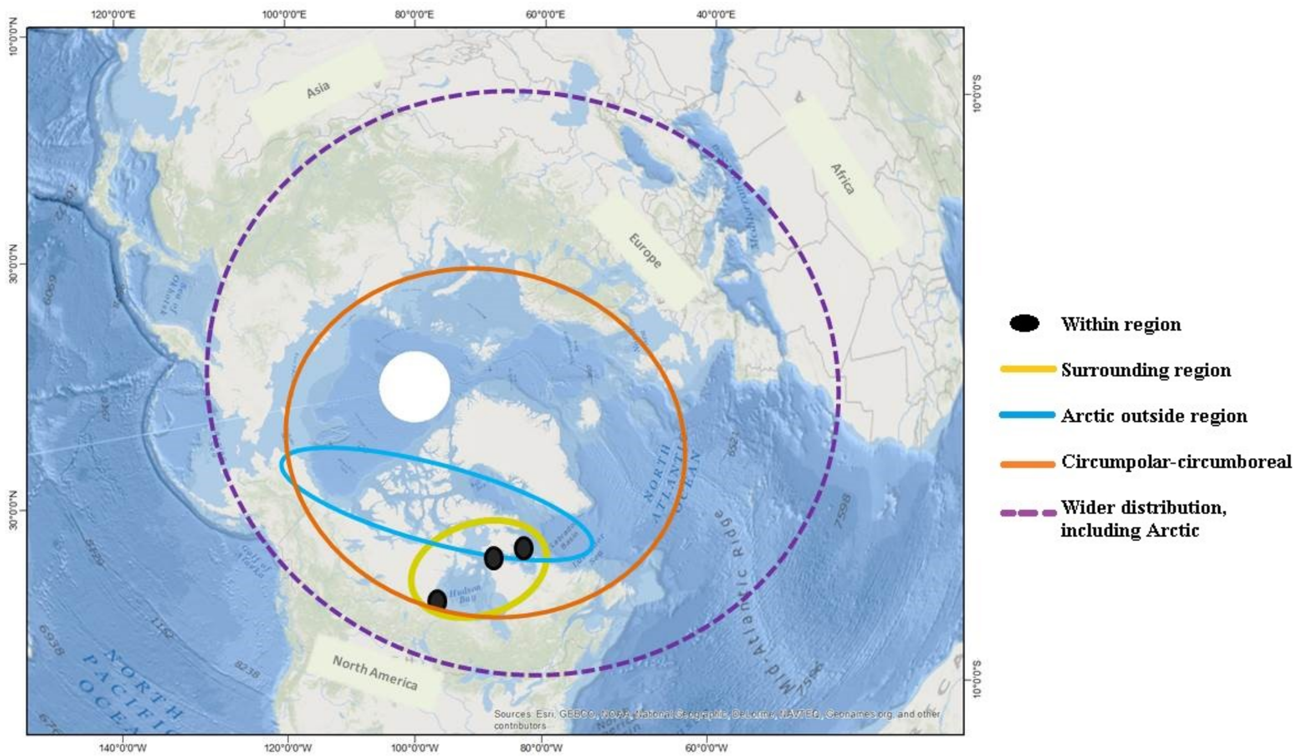


Figure 8: Schematic showing approximate regions corresponding to categories of distribution patterns used to define the closest records for the species found in the ports surveyed: 1) within region, 2) surrounding region, 3) Arctic outside region, 4) circumpolar/ circumboreal, 5) wider distribution, including Arctic.

RESULTS

We identified 236 taxa from surveys in the ports of Churchill (Ch), Deception Bay (DB) and Iqaluit (Iq) (see Appendix II for the complete list of genus and species). Of the taxa identified, 14.4% were not previously recorded within a given port, while 7.2% (17 taxa, mostly Polychaeta) were not previously recorded from the larger surrounding regions of each port (Table 2). A total of seven species (3%) were records found for the first time in Canadian Arctic waters. The most widely represented phylum was Annelida (Polychaeta) in all three ports (Ch=56.2%, DB=47.8%, Iq= 44.8%), followed by Arthropoda (Crustacea) (Ch=13.5%, DB=18.2%, Iq= 26.4%), and Mollusca (Ch=12.4%, DB=20.1%, Iq= 19.5%) Figure 9. The genus and species identified accounted for the 62.7% (n=142), 63.9% (n=249), and 62.6% (n=139) of the total taxa identified for Churchill, Deception Bay and Iqaluit respectively. Some groups like Oligochaeta, Nematoda, Nemertea and Copepoda (Harpacticoida and Calanoida) were not identified further due to the high level of specialization required to identify them, even though their presence and abundance were high in the three ports. A total of 10.2% of the taxa (mostly polychaetes) were shared among the three ports. The similarities between ports for species composition were: S_{Ch-DB}=40.3, S_{Ch-Iq}=33 and S_{DB-Iq}=39.8 (where S=0 when samples have no species in common and S=100 when they are identical).

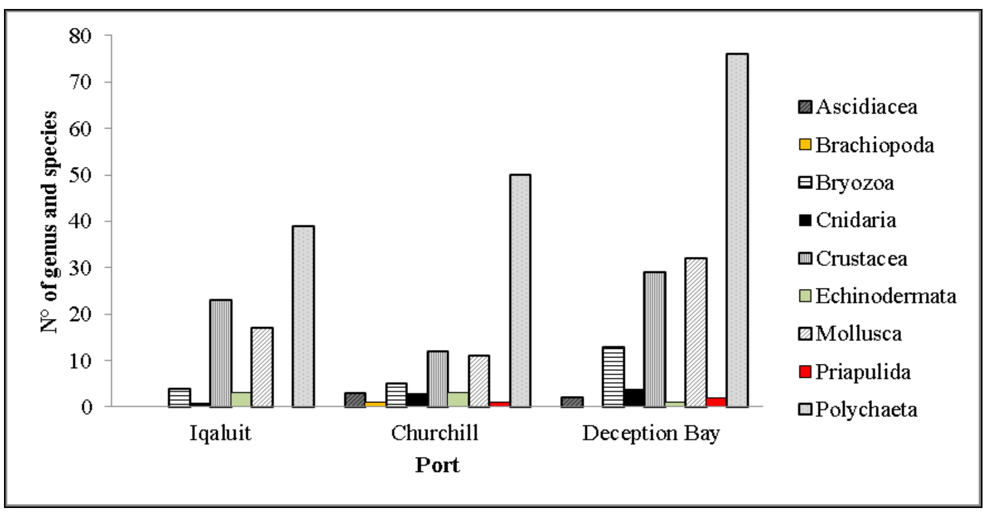


Figure 9: Histogram showing the taxonomic composition sampled by core for the ports of Iqaluit, Churchill and Deception Bay.

Table 2: New species records with known closest region distribution and comments about presence in the region of study. Port: Churchill (Ch), Deception Bay (DB), Iqaluit (Iq). Regions of known distribution: Other Canadian Arctic Regions (CA), West Greenland (WG), European/Asian Arctic (EAA), Temperate North America (TNA), Other Temperate regions (OT). Category of distribution pattern: Arctic Outside Region (AOR), Circumpolar-Circumboreal Distribution (CCD), Wider Distribution including Arctic region (WD). Origin: Increased Survey Effort (ISE), Cryptogenic (Cr). References: Ocean Biogeographic Information System (OBIS), Sea Life Base (SLB).

Taxa	Genus - Species	Port	Regions of known distribution					Distrib. pattern	Origin	References
			CA	WG	EAA	TNA	OT			
	Aricidea cf. hartmani	Ch, DB	x		x				Cr	MacDonald *et al.* (2010), OBIS
	Bipalponephtys neotena	Ch, DB	x		x	x		WD	ISE	Appy *et al.* (1980); Atkinson and Wacasey (1989b); Cusson *et al.* (2007); MacDonald *et al.* (2010); OBIS
	Dipolydora socialis group	DB				x	x		Cr	Dahle *et al.* (1998); OBIS, SLB
	Lumbrineris cf. zatsepini	DB			x				Cr	Oug (2011)
Polychaeta	*Owenia borealis*	Iq			x				Cr	Koh and Bhaud (2003); Jirkov and Leontovich (2012)
	Paradexiospira (Paradexiospira) violaceus	DB	x	x	x			CCD	ISE	Wesenberg-Lund (1950); Knight-Jones *et al.* (1991); Cusson *et al.* (2007); OBIS
	Paraonides nordica	Iq, Ch, DB		x	x				Cr	Strelzov (1979); OBIS
	Pholoe longa	Ch, DB	x	x		x		AOR	ISE	Pocklington (1989); Pettibone (1992); OBIS
	Streptospinigera niuqtuut	DB	x			x		AOR	ISE	Olivier *et al.* (2013)
	Syllides sp.	Iq, Ch, DB	x		x			CCD	ISE	Ramos *et al.* (2010); OBIS
Crustacea	*Onisimus sextoni group*	DB			x		x		Cr	Lowry and Stoddart (1993); Vader *et al.* (2005)
	Rostroculodes schneideri	DB	x		x	x		CCD	ISE	Stebbing (1906); Castillo (1976); Kennedy (1985); OBIS
	Einhornia arctica	Iq	x	x	x	x		CCD	ISE	Kluge (1975)
Bryozoa	*Lichenopora crassiuscula*	Iq	x	x	x			CCD	ISE	Kluge (1975)
	Schizoporella crustacea	DB	x	x	x			CCD	ISE	Kluge (1975); OBIS
Ascidiacea	*Heterostigma* sp.	DB			x	x			Cr	Van Name (1945); OBIS
Mollusca	*Axinulus* sp.	DB	x		x	x	x	WD	ISE	Bernard (1979); OBIS

The taxa accumulation plots for individual ports and the three ports combined did not reach an asymptote, suggesting that sampling effort is still insufficient for characterizing the full extent of biodiversity at these locations (Figure 10). When calculating the species richness estimator Chao2 for the three ports combined to estimate expected total species numbers, the expected number of species for an infinite number of samples according was 346.2, exceeding the total number of observed species by almost 32%, clearly showing that expected number of genus and species is quite different from what was observed.

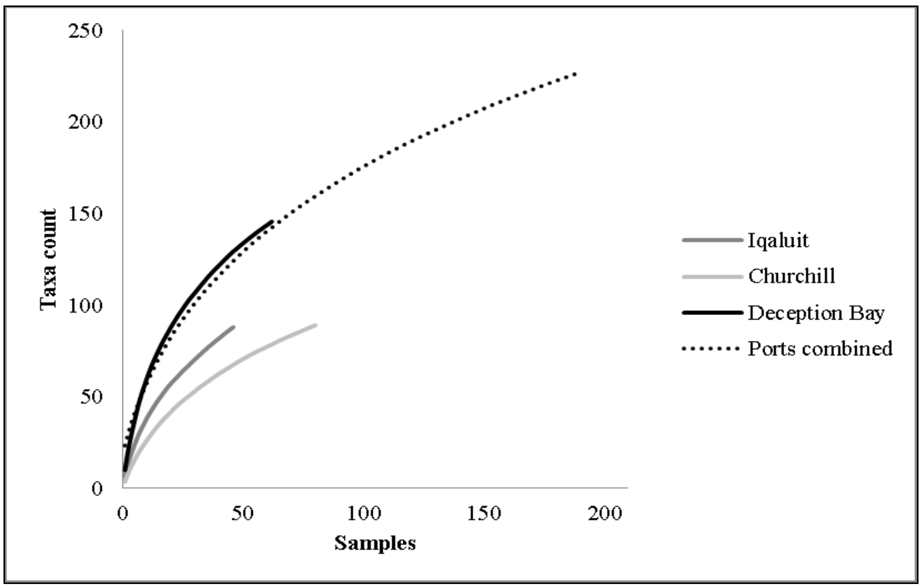


Figure 10: Randomized taxa accumulation curves found in sample data gathered from the three ports studied.

Overall, more than 80% of the taxa analyzed had historical records for being ‘within region’ (Figure 11). The remaining taxa were previously found in other Arctic regions, either in the ‘surrounding’ areas of the ports sampled, ‘Arctic outside region’, ‘circumpolar-circumboreal’ region or an even ‘wider distribution including Arctic’. The majority of new records found are most likely explained by increased survey effort. None of the species were found to have only Temperate North America, Asia, or Europe as the closest region for previous records. Below we summarize and describe our findings for key taxa, in particular those which represent new records in a given location (for a complete list of species and distribution references see Appendix II).

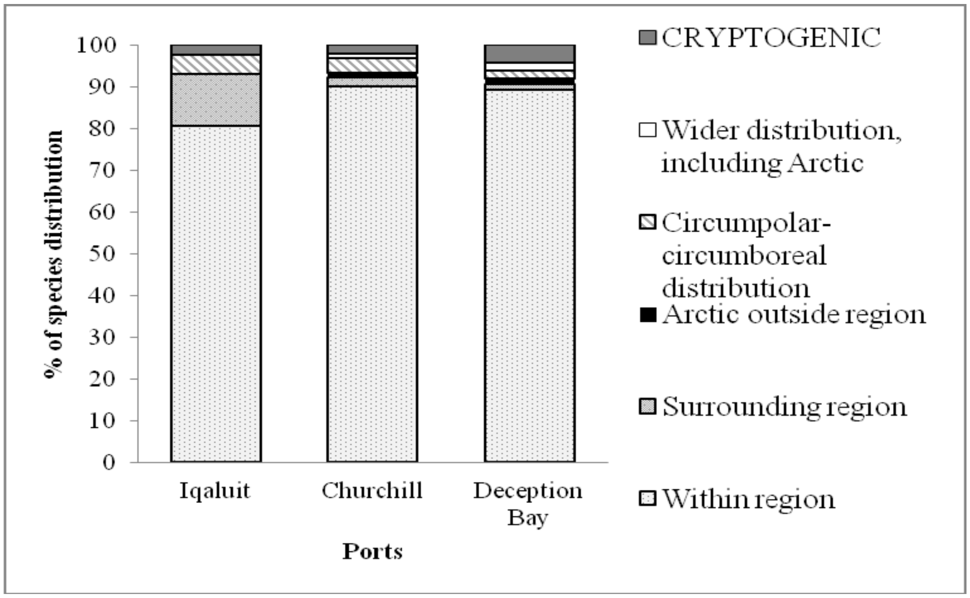


Figure 11: Percentage of species distribution by port, divided in categories of distribution patterns: 1) cryptogenic, 2) wider distribution, including Arctic, 3) circumpolar-circumboreal distribution, 4) Arctic outside region, 5) surrounding region, 6) within region.

Annelida (Polychaeta)

Fifty-eight species and 43 polychaete genera were collected. Nine species and one genus represent new records within a given port region and adjacent surrounding region (Table 2).

Two species, *Streptospinigera niuqtuut* (Syllidae) found in Churchill and Deception Bay and *Pholoe longa* (O.F. Müller, 1776) (Pholoidae) found in Deception Bay, had their closest previous records in the Canadian Arctic outside the region, but do not appear to have a wider Arctic or circumpolar/circumboreal distribution. Interestingly both species have also been recorded in temperate regions of North America and/or Europe.

One species and one genus had their closest previous records in other Arctic regions, including the European and Asian Arctic, the Canadian Arctic and West Greenland; both tended to have a more extensive circumpolar-circumboreal distribution. These included *Paradexiospira* (*Paradexiospira*) *violaceus* (Levinsen, 1883) (Spirorbidae) found in Deception Bay and *Syllides* sp. Örsted, 1845 (Syllidae) found in Iqaluit, Churchill and Deception Bay.

One species, *Bipalponepthys neotena* (Noyes, 1980) (Nephtyidae) found in Churchill and Deception Bay, had a wider historical distribution, including Temperate North American waters (Atlantic and Pacific) and other Arctic regions.

Five polychaetes species were found for the first time in Canadian Arctic waters, having historical records elsewhere. These included *Aricidea cf. hartmani* Strelzov, 1968 (Paraonidae) found in Churchill and Deception Bay, *Dipolydora socialis* group (Schmarda, 1861) (Spionidae) found in Deception Bay, *Lumbrineris cf. zatsepini* Averincev, 1989 (Lumbrineridae) found in Deception Bay, *Owenia borealis* Koh, Bhaud and Jirkov, 2003 (Oweniidae) found in Iqaluit and *Paraonides nordica* Strelzov, 1968 (Paraonidae) found in all three ports. Although *A. cf. hartmani* has previously been found in the Canadian Arctic, it was only recently recorded (2010) with uncertainty in its native status, and therefore is not considered a historical record.

Summarizing, most of the polychaetes listed above as being new records within the port regions, are unlikely to be non-indigenous since they have been found historically widely distributed throughout Canadian Arctic waters and in many cases, also in other Arctic or sub-Arctic waters. Exemptions to this are the *D. socialis* group, *L. cf. zatsepini*, *O. borealis* and *P. nordica* that were found for the first time in the Canadian Arctic; and *A. cf. hartmani* that was recently found in Arctic Canada Basin. Given that all these species come from complicated taxonomic groups and their distributions are not well known, we have classified them as cryptogenic, as is already the case for the *D. socialis* group, which has previously been reported as cryptogenic in USA Pacific waters (Table 3).

Five polychaete species having historical records within the port region and considered to be in their native range were found in different NIS lists in other parts of the world as cryptogenic, questionable status or established species (Table 3).

Table 3: List of species present in this survey reported as established NIS, cryptogenic or questionable elsewhere in the world. Modified from (Çinar, 2013).

Species	Status in present survey	Status in other regions	References
Celleporella hyalina	Native	Cryptogenic in Alaska	Ruiz *et al.* (2006)
Dipolydora socialis	Cryptogenic	Cryptogenic in Australia – USA Pacific	Hayes *et al.* (2005); Boyd *et al.* (2002)
Dipolydora quadrilobata	Native	Cryptogenic in North Atlantic / North Pacific	Hines *et al.* (2000a)
Harmothoe imbricata	Native	Established? / cryptogenic in USA Atlantic	Ruiz *et al.* (2000)
Nephtys ciliata	Native	Questionable in Black Sea	Gomoiu *et al.* (2002)
Glycera capitata	Native	Questionable in Black Sea	Gomoiu *et al.* (2002)
Opercularella lacerata	Native	Cryptogenic in Alaska	Hines *et al.* (2000b)
Pygospio elegans	Native	Cryptogenic in USA Atlantic and Pacific	Ruiz *et al.* (2000); Boyd *et al.* (2002)

Arthropoda (Crustacea)

Forty-five arthropod taxa were collected. Two species, *Onisimus sextoni* group Chevreux, 1926 (Uristidae) and *Rostroculodes schneideri* (Sars G.O., 1895) (Oedicerotidae), were found in Deception Bay and represent new records within the port region and adjacent surrounding region (Table 2). *R. schneideri* has previously been found in other Arctic regions, including Canada, Europe, and Asia, extending into temperate areas along the Canadian north-Atlantic coast; thus, it is unlikely to be non-indigenous to the region. The case is different for *O. sextoni* group. This group appears to have a circumpolar-circumboreal distribution given that it has been recorded in high-latitude northern seas, Greenland, Iceland and Norway. However, given that the information on the distribution of this genus is limited and this is the first record of its occurrence in Canadian Arctic waters, we have categorized it as cryptogenic.

Brachiopoda

Only one species of Brachipoda was collected, *Hemithiris psittacea* (Gmelin, 1790) (Hemithirididae) found in Churchill, and is already known to occur within the port region.

Bryozoa

Nineteen bryozoans were identified. Three species represent new records within the ports regions and the adjacent surrounding region. These included *Einhornia arctica* (Borg, 1931) (Electridae) found in Iqaluit, *Lichenopora crassiuscula* Smitt, 1867 (Lichenoporidae) found in Iqaluit and *Schizoporella crustacea* (Smitt, 1868) (Schizoporellidae) found in Deception Bay (Table 2). These species have, however, been found in other Arctic regions (Archipelago of Canadian Islands, Davis Strait and West Greenland, including European Arctic), showing a circumpolar-circumboreal distribution. Thus, these species are unlikely to be non-indigenous to the region.

One bryozoan, *Celleporella hyalina* (Linnaeus, 1767) (Hippothoidae), having historical records within the port region and considered to be in their native range, was found on an NIS list elsewhere in the world as cryptogenic (Table 3).

Cephalorhyncha (Priapulida)

Two species and one genus of the Priapulidae family were found: *Halicryptus spinulosus* von Siebold, 1849 in Churchill, *Priapulus caudatus* Lamarck, 1816 in Deception Bay, and *Priapulus* sp. Lamarck, 1816 in Deception Bay. These taxa are known to be native and had previously been found historically within the region of each port.

Chordata (Ascidiacea)

Four taxa of sea squirts were identified. Three of them are known to occur within the port regions for Churchill and Deception Bay. The fourth species, *Heterostigma* sp.

Ärnbäck-Christie-Linde, 1924 (Pyuridae), was new to the Deception Bay port region and adjacent surrounding areas (Table 2). This genus is likely to have a circumpolar-circumboreal distribution since it has been recorded from Norway and is described as having a wide Arctic distribution, reaching the Atlantic coast of North America. However, given that the information on the distribution of this genus is limited and this is the first record of its occurrence in Canadian Arctic waters, we have categorized it as cryptogenic.

Cnidaria

Four species of cnidarians were collected between Churchill and Deception Bay, and four specimens were identified to genus level between Iqaluit and Deception Bay samples. All specimens of Cnidaria had previously been found in the region of each port as well as in the larger surrounding region since they had been previously identified in the Hudson Complex, and are known to be native to the region.

One cnidarian, *Opercularella lacerata* (Johnston, 1847) (Campanulinidae), having historical records within the port region and considered to be in their native range, was found on an NIS list elsewhere in the world as cryptogenic (Table 3).

Echinodermata

Five echinoderm taxa were identified. All of them are known to be distributed throughout the area and have been frequently found historically within the port regions or adjacent surrounding regions.

Mollusca

Forty-five molluscan taxa were identified among the three ports. One genus, *Axinulus* sp. Verrill and Bush, 1898 (Thyasiridae), represents a new record within the Deception Bay port region and adjacent surrounding region. This genus is known for having an Arctic distribution, including Canadian Arctic and Alaska, extending into temperate areas along the north Atlantic and the Mediterranean Sea (Table 2). Thus this genus is unlikely to be non-indigenous to the region.

DISCUSSION

This study provides the first published benthic invertebrate survey for NIS in coastal regions of the Canadian Arctic (the longest coastline in the world) that incorporates historical survey information in order to identify new records. Approximately 15% of the taxa identified can be considered new records within the port regions surveyed and approximately 8% within the more extensive adjacent surrounding regions based on our criterion for cross referencing and comparing current and historical species lists. The most likely explanation for the majority of these new occurrences is increased survey effort in the various study locations, which is supported by our species accumulation curves that showed a much higher expected total number of species that the number actually observed. Taxa that were new for a given port, but were previously recorded in the surrounding region, are clearly the effect of increased survey effort. The occurrence of taxa that were previously recorded outside the surrounding region can also be explained with the same hypothesis when looking at their distribution patterns. It is likely that these species occurred previously in the region of study but were not sampled or identified due to the low sampling effort in the region. Further sampling would be expected to increase the number of taxa known to occur in the entire study area. Our results suggest that the coastal region of the Canadian Arctic might be much richer that we indicate here. The very low survey effort in the Arctic, the underestimated diversity, and expected increases in activity in the Arctic means a comprehensive understanding of marine biodiversity is more important today than ever (Archambault *et al.*, 2010; MacDonald *et al.*, 2010; Carr, 2012; Snelgrove *et al.*, 2012). We identified one ascidia, *Heterostigma* sp., one amphipod, *Onisimus sextoni* group, and several polychaetes that represent new mentions for the Canadian Arctic, including: *Aricidea cf. hartmani*, *Dipolydora socialis* group, *Lumbrineris cf. zatsepini*, *Owenia borealis* and *Paraonides nordica*. These taxa have distributions elsewhere in the Arctic realm and in some cases within temperate waters (Van Name, 1945; Strelzov, 1979; Lowry & Stoddart, 1993; Dahle *et al.*, 1998; Koh & Bhaud, 2003; Vader *et al.*, 2005; MacDonald *et al.*, 2010; Oug, 2011; Jirkov & Leontovich, 2012); however, distributional information is sporadic at best. Generally speaking, historical records for the majority of species in most shallow-water communities are unavailable (Carlton, 1996b); hence, the fact that they have never been described for the Canadian Arctic may be a consequence of lack of sampling efforts. It has, however, been recommended that the discovery of previously unrecognized species in regions impacted by ballast water release should be viewed critically as potential invasions (Carlton & Geller, 1991). Hence, as a result of the limited distributional information and the lack of population genetics information, we cannot confidently categorize these taxa as native or introduced and have therefore classified them as cryptogenic. Recent use of molecular techniques may help resolve some cryptogenic invasions, especially those involving sibling species complexes (Geller, 1996). Indeed, of note, is that one of these taxa, the *D. socialis* group, is already considered to be a cryptogenic species in Australia and in some places in the Northeast Pacific (Boyd *et al.*, 2002; Hayes *et al.*, 2005). Also of note is the case of *A. cf. hartmani*, which has been collected in the Canada Basin by MacDonald *et al.* (2010). They explain that it is likely that this species has not been sampled before due to low sampling effort, but they postulate that its presence could also be due to range changes that have occurred because of climate change, dispersal of organisms through ballast water, or other mechanisms. Further research will be required to better understand the status of all of these cryptogenic taxa.

Among the major taxonomic groups we identified by the core sampling, the polychaetes were the most diverse and abundant in all three ports and were the group for which we found the highest numbers of new records. There are also a number of interesting notes regarding the new records for this taxonomic group. Recently, Olivier *et al.* (2013) described a new Syllidae species, *Streptospinigera niuqtuut*, in the Canadian High Arctic archipelago and the northern Atlantic coast of the United States. Until now, it was only found in deeper stations (≥ 175 m), but we collected *S. niuqtuut* in shallow coastal waters (e.g., 10.6 m in the Deception Bay port).

Groups like Oligochaeta, Nematoda, Nemertea and Copepoda (Harpacticoida and Calanoida) were present and in high abundance in most of our samples. This is consistent with other studies which have shown these groups to be highly abundant. For example, (Giere, 2008) found that in meiofaunal samples, the number of species of nematodes often exceeded that of the other groups put together by an order of magnitude. Aside from nematodes, harpacticoid copepods are usually the next most abundant meiobenthic animal in marine samples (Giere, 2008). Given this information, it is clear that we are missing a large part of the biodiversity in our sample analyses. However, these taxonomic groups require a high level of specialization to identify them morphologically, and genetic methods are frequently the only adequate means for achieving taxonomic distinction. Approximately 950 species of harpacticoid copepods belonging to 13 families are known to have invaded freshwater biotopes (Giere, 2008), but for the other groups invasions are rarely reported (Rilov & Crooks, 2008). This does not necessarily mean that invasions have not occurred, but may be related to the phenomenon referred to as the "smalls rule of invasion ecology," defined as an inverse correlation of body size with the ability to be recognized as non-native (Carlton, 2009). These groups we are referring to here could easily be part of this phenomenon, raising concerns about the potential consequences of actually having NIS, but not being able to detect them for lack of information or adequate tools.

We have highlighted that the coastal region of the Canadian Arctic is likely to be at risk for introductions of NIS, but we also need to realize that the species native to the Arctic can also be non-indigenous elsewhere in the world, especially with the increasing shipping activity expected in the future (Smith & Stephenson, 2013). Eight species found in our sampling have been found to be established NIS (non-native species with self-maintaining populations), cryptogenic, or have a questionable status somewhere else in the world (Table 3) (Carlton, 1996b). All of these polychaetes, except one (*Dipolydora socialis* group), are within their historical native range. The knowledge that there are species in their native range in the Arctic that are on NIS lists in other parts of the world, poses a different point of view. Chan *et al.* (2013) emphasize the importance of estimating the relative invasion risk at major ports and identify risky transit pathways for the Canadian Arctic, and Casas-Monroy *et al.* (2014) indicate that it is unlikely that the Canadian Arctic serves as a source of NIS to other locations because the volume of ballast water leaving the Canadian

Arctic to be dumped elsewhere is very low compared to other Canadian regions. Our findings, however, suggest we also need to explore a different perspective and be aware that the Arctic could be a potential source of NIS for ports elsewhere in the world, increasing the importance of establishing a baseline for these areas of the ocean.

Locke and Hanson (2009) propose a framework for rapid response for non-indigenous aquatic species in Canada that includes a series of pre- and post- invasion actions. One of the pre-invasion planning steps is the detection phase where they suggest conducting ecological inventories when necessary to establish baseline information on native and NIS populations. In order to determine if a species has newly arrived in a location, they state that it is absolutely necessary to know what was previously present. In order to do that, monitoring surveys should be designed to provide several years of baseline information for poorly studied areas or taxa. Our work clearly shows that we are still missing much of the baseline information required for even identifying which species are native. We found 34 new records within the three ports studied, which accounts for 14.4% of taxa found. Thus, we are still in one of the first stages in a pre-invasion framework. This highlights the importance of baseline studies such as this one, especially in remote places with a risk of invasion in the future. Since preventing the introduction of NIS remains the most effective course of management (Sylvester *et al.*, 2011), surveys aimed at detecting incipient invasions are critical given that any kind of intervention can only proceed after an alien invasion has been detected (Bogich *et al.*, 2008).

The number of non-indigenous species reported in Polar Regions is low compared with other temperate regions (Elrich *et al.*, 1989; Niimi, 2004; Ruiz & Hewitt, 2009) and may, in part, be due to insufficient research effort (Niimi, 2004; Ruiz & Hewitt, 2009). Nevertheless, we cannot take for granted that Polar Regions are exempt from introductions (Ashton *et al.*, 2008b; Ruiz & Hewitt, 2009; Smith *et al.*, 2011; Lassuy & Lewis, 2013). Currently, access to Arctic ports is limited by a short navigation season but prospects for a longer navigation season are likely to improve with predicted future temperature and ice-free season increases, particularly at higher latitudes (Vermeij & Roopnarine, 2008; Smith

& Stephenson, 2013). Under this scenario, the risk of introduction increases in Arctic regions (Cheung *et al.*, 2009; Ware *et al.*, 2014).

The Canadian Arctic is a vast region with a very high potential for resource exploitation. More than 25 large-scale marine-development projects are expected to be operational by 2020 in Canada's North, which would represent up to 433 shipments per year (mining developments only), and the region is expected to experience an unprecedented increase in industrial development over the next 10 years (Gavrilchuk & Lesage, 2014). At the same time, we know that this large region has undersampled coastlines, especially for invertebrate benthic fauna, whose distributions are still incompletely known. New species and distributions continue to be described (Olivier *et al.*, 2013). Our study provides a benchmark for early detection for benthic invertebrates in coastal port regions of the Canadian Arctic and for the Arctic itself. It also demonstrates the importance of generating representative baseline data. Monitoring surveys and early detection efforts involve significant costs and are highly labor intensive but provide a great opportunity for identifying native and introduced taxa, crucial to analyzing the changes taking place along one of the longest coastlines in the world. While the present survey did not detect any known non-indigenous species, we encourage more studies like this one since significant discoveries are likely to be made regarding both native and non-indigenous species.

ACKNOWLEDGEMENTS

The authors would like to thank three anonymous reviewers for thoughtful comments on the manuscript. Many people have been involved for this project to take place, and without them it would not have been successful. Special thanks to K. Adair for taking care of all the logistic work for field work and always be present with everything we need. We want to thank the field team: C. Basler, J. Batstone, C. Binet, S. Bourgeois, C. Grant, F. Hartog, R. Felix, L. Fishback, K. Jansen, Z. Martin, F. McCaan, C. Pokiak, P. Robichaud, D. Stewart, J. Stewart, B. Townsend, M. Wetton, S. Wiley, G. Williams, and all the local people that was so helpful: D. Kaludjak, K. Lindell, A. Williams and J. Williams (community of Iqaluit); C. Alaku, C. Kadjulik, K. Ningiurluut, K. Okituk, C. Okituk, L. Yuliusie and A. Keatainak (community of Salluit); A. Allianaq, T.R. Avingaq, G. Illupaalik, J. Kukkik, A. Kutiq and T.A. Taqqaugaq (communities of Igloolik and Hall Beach). We also want to thank all the people that have helped doing sorting at the lab: O. Cloutier, J.A. Dorval, A. Drouin, J. Joseph, N. Le Corre, V. Liao, M. Maury, A. Pilon, J. Ruest and P. Tremblay. Special thanks to L. Tréau de Coeli and L. de Montety for doing the sample identifications. We want to thank also to Dr. J. Blake for verifying polychaetes samples and Dr. M. Tatian for verifying ascidian samples, and to Dr. M.A. Tovar-Hernandez and Dr. G. San Martin for making valuable comments and answering to our many questions. We are grateful for funding from the Canadian Aquatic Invasive Species Network (CAISN) and the Natural Sciences and Engineering Research Council (NSERC), and for the great support we received from Polar Continental Shelf Program (PCSP), Aquatic Climate Change Adaptation Services Program (ACCASP), Nunavut Wildlife Management Board (NWMB), and the Department of Fisheries and Oceans Canada (DFO), as well as Quebec-Ocean.

APPENDIX I: REFERENCES HISTORICAL DATABASE

Complete list of all references used in the cross referencing protocol for comparison of temporal changes in species presence through comprehensive historical database of benthic species from throughout the Canadian Arctic.

References	**References**
Aitken and Gilbert (1986)	Olivier *et al.* (2013)
Aitken *et al.* (1988)	Osburn (1932)
Atkinson and Wacasey (1989a)	Oug (2011)
Atkinson and Wacasey (1989b)	Pettibone (1956)
Atkinson and Wacasey (1989c)	Pettibone (1992)
Appy *et al*. (1980)	Piepenburg *et al.* (2011)
Baker (1989)	Pocklington (1989)
Baker *et al.* (1994)	Powell (1968)
Berkeley and Berkeley (1943)	Ramos *et al.* (2010)
Bernard (1979)	Samuelson (2001)
Blake and Dean (1973)	Stebbing (1906)
Blake (1991)	Strelzov (1979)
Conover and Stewart (1978)	Thomson *et al.* (1986)
Ellis (1957)	Vader *et al.* (2005)
Ellis (1960)	Van Name (1945)
Grainger (1954)	Wacasey (1979)
Helgason *et al.* (1990)	Wacasey *et al*. (1980)
Jirkov and Leontovich (2012)	Wesenberg-Lund (1950)
Kennedy (1985)	Ocean Biogeographic Information System (OBIS)
Koh and Bhaud (2003)	Arctic Ocean Diversity (ArcOD)
Kluge (1975)	Sea Life Base (SLB)
Knight-Jones *et al.* (1991)	Global Biodiversity Information Systems (GBIF)
Lawrence and Baker (1995)	National Museum of Natural History (Smithsonian database)
Lowry and Stoddart (1993)	
MacDonald *et al.* (2010)	

APPENDIX II: GENUS AND SPECIES IN CORE SAMPLES (IQALUIT, CHURCHILL AND DECEPTION BAY)

Complete list of all genus and species identified in alphabetic order. Authors, ports where they were found, closest region for previous records, category of distribution pattern, comments about the probable origin and references are reported. Category of distribution pattern: Within Region (WR), Surrounding Region (SR), Arctic Outside Region (AOR), Circumpolar-Circumboreal Distribution (CCD), Wider Distribution including Arctic region (WD). Origin: Increased Survey Effort (ISE), Cryptogenic (Cr). References: Ocean Biogeographic Information System (OBIS), Sea Life Base (SLB), Global Biodiversity Information Systems (GBIF), National Museum of Natural History (Smithsonian).

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Annelida - Polychaeta							
Ampharete acutifrons (Grube, 1860)		x		Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB, ArcODiv
Ampharete finmarchica (M. Sars, 1864)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Berkeley and Berkeley (1943), Wesenberg-Lund (1950), Grainger (1954), Pettibone (1956), Blake and Dean (1973), Pocklington (1989), ArcODiv
Ampharete sibirica Wirén, 1883			x	Hudson complex	WR		Wacasey *et al.* (1976), Atkinson and Wacasey (1989c)
Ampharete sp. Malmgren, 1866	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Aphelochaeta sp. [1] Blake, 1991			x	West Greenland, North Sea, Temperate North America, Laptev Sea (Arctic)	WD	ISE	Blake (1991), OBIS, ArcOD, GBIF
Apistobranchus tullbergi (Théel, 1879)			x	Hudson complex	WR		SLB, ArcOD

[1] *Aphelochaeta* may have been reported previously as *Tharyx*. It was considered in the "within region" category because *Tharyx* is native to the region.

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Arenicola marina (Linnaeus, 1758)		x		Hudson complex	WR		OBIS, ArcOD
Aricidea cf. hartmani Strelzov, 1968		x	x	Barents Sea, High Canadian Arctic		Cr	MacDonald *et al.* (2010), OBIS
Aricidea nolani Webster & Benedict, 1887	x		x	Frobisher Bay	WR		Pocklington (1989), OBIS
Aricidea sp. Webster, 1879	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Asabellides sp. Annenkova, 1929			x	Hudson complex	WR		Atkinson and Wacasey (1989c), OBIS
Axiothella catenata (Malmgren, 1865)	x		x	Davis Strait - Hudson complex	SR (Iq) / WR (DB)	ISE (Iq)	Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS, SLB
Bipalponephtys neotena (Noyes, 1980)		x	x	Beaufort Sea, White Sea, Gulf St. Lawrence, Bay of Fundy	WD	ISE	Appy *et al* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), MacDonald *et al.* (2010), OBIS
Brada villosa (Rathke, 1843)	x			Frobisher Bay	WR		Wacasey *et al.* (1980), SLB
Capitella capitata (Fabricius, 1780)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Capitella sp. Blainville, 1828	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), OBIS, SLB
Chaetozone sp. Malmgren, 1867	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), OBIS
Chone sp. Krøyer, 1856	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Circeis spirillum (Linnaeus, 1758)			x	Hudson complex	WR		Pocklington (1989), OBIS
Cistenides granulata (Linnaeus, 1767)		x	x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Cistenides hyperborea Malmgren, 1866		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Cossura sp. Webster & Benedict, 1887			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Dipolydora caulleryi (Mesnil, 1897)		x	x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Dipolydora quadrilobata (Jacobi, 1883)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Cusson *et al.* (2007), Smithsonian, SLB
Dipolydora socialis group (Schmarda, 1861)			x	Barents Sea, Atlantic and Pacific ocean		Cr	Dahle *et al.* (1998), OBIS, SLB, ArcOD
Dipolydora sp. Verrill, 1881			x	Hudson complex	WR		Smithsonian, SLB, ArcOD
Erinaceusyllis sp. San Martín, 2005			x	Hudson complex	WR		SLB, ArcOD
Eteone sp. Savigny, 1818	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007)Cusson et al 2007, OBIS
Euchone analis (Kröyer, 1865)	x			Frobisher Bay	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Euchone papillosa (Sars, 1851)			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Euchone sp. Malmgren, 1866	x			Frobisher Bay	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Eusyllis sp. Malmgren, 1867			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Exogone (Exogone) nadina Örsted, 1845			x	Hudson complex	WR		Wacasey (1979), OBIS, ArcOD
Exogone (Parexogone) hebes (Webster & Benedict, 1884)			x	Frobisher Bay, Canadian Arctic Ocean, Eastern Canadian Arctic, West Greenland	SR	ISE	Wesenberg-Lund (1950), Pocklington (1989)
Exogone (Parexogone) longicirris (Webster & Benedict, 1887)	x	x	x	West Greenland Shelf, Iceland, Subarctic Europe, Maine USA		Cr	Helgason *et al.* (1990), OBIS,
Exogone sp. Örsted, 1845		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Galathowenia oculata (Zachs, 1923)		x		Hudson complex	WR		Cusson *et al.* (2007), OBIS
Gattyana cirrhosa (Pallas, 1766)		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Gattyana sp. McIntosh, 1897		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Glycera capitata Örsted, 1843		x	x	Hudson complex	WR		OBIS, SLB, ArcOD
Glycera sp. Savigny, 1818		x		Hudson complex	WR		OBIS, SLB, ArcOD
Harmothoe imbricata (Linnaeus, 1767)		x		Baffin Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Harmothoe sp. Kinberg, 1856	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
							Wacasey (1989c), Cusson *et al.* (2007), OBIS
Lanassa sp. Malmgren, 1866		x		Hudson complex	WR		Wacasey (1979), Cusson *et al.* (2007)
Laonome kroyeri Malmgren, 1866			x	Hudson complex	WR		SLB, ArcOD
Laphania boecki Malmgren, 1866	x			Frobisher Bay	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), SLB
Lumbrineris cf. zatsepini Averincev, 1989			x	Barents Sea, Norwegian waters, Arctic shallow waters		Cr	Oug (2011)
Lysippe labiata Malmgren, 1866			x	Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Lysippe sp. Malmgren, 1866			x	Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Manayunkia aestuarina (Bourne, 1883)			x	Hudson complex	WR		Baker (1989), ArcOD
Manayunkia sp. Leidy, 1859		x	x	Hudson complex	WR		Baker (1989), ArcOD
Micronephthys sp. Friedrich, 1939		x		Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Microphthalmus aberrans (Webser & Benedict, 1887)		x		Hudson complex	WR		SLB
Microphthalmus sp. Mecznikow, 1865	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), SLB
Microspio sp. Mesnil, 1896		x		Baffin Frobisher Bay	SR	ISE	Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Myrianida prolifer (O.F. Müller, 1788)		x		Hudson complex	WR		OBIS, ArcOD

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Nephtys ciliata (Müller, 1788)	x	x		Baffin Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Samuelson (2001), Cusson *et al.* (2007), OBIS, SLB
Nephtys incisa Malmgren, 1865		x		Hudson complex	WR		Cusson *et al.* (2007), SLB
Nereimyra sp. Blainville, 1828			x	Hudson complex	WR		Wacasey *et al* (1976), Atkinson and Wacasey (1989c), OBIS, SLB
Nereis sp. Linnaeus, 1758			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), Smithsonian, OBIS
Ophelia limacina (Rathke, 1843)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Samuelson (2001), Cusson *et al.* (2007), OBIS, SLB
Ophelia sp. Savigny, 1822			x	Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Samuelson (2001), Cusson *et al.* (2007), OBIS, SLB
Ophryotrocha sp. Claparède & Mecznikow, 1869		x	x	Hudson complex	WR		Berkeley and Berkeley (1943), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Owenia borealis Koh, Bhaud & Jirkov, 2003	x			North Atlantic, Norwegian waters, Greenland, Barents Sea		Cr	Koh and Bhaud (2003), Jirkov and Leontovich (2012)
Paradexiospira (Paradexiospira) *violaceus* (Levinsen, 1883)			x	Alaska, European Arctic, Western Canadian Arctic, West Greenland	CCD	ISE	Wesenberg-Lund (1950), Knight-Jones *et al.* (1991), Cusson *et al.* (2007), OBIS, GBIF
Paraonides nordica Strelzov, 1968	x	x	x	West Greenland Shelf / Barents Sea		Cr	Strelzov (1979), OBIS

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Paraonis sp. Cerruti, 1909		x		Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007)
Pholoe longa (O.F. Müller, 1776)		x	x	Southern Labrador, High Eastern Arctic, West Greenland Shelf, Beaufort Sea	AOR	ISE	Pocklington (1989), Pettibone (1992), OBIS
Pholoe minuta (Fabricius, 1780)			x	Hudson complex	WR		Atkinson and Wacasey (1989c), OBIS, SLB
Pholoe sp. Johnston, 1839	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Phyllodoce groenlandica Örsted, 1842			x	Hudson complex	WR		Cusson *et al.* (2007), OBIS
Phyllodoce maculata (Linnaeus, 1767)			x	Hudson complex	WR		Berkeley and Berkeley (1943), SLB
Phyllodoce sp. Lamarck, 1818		x	x	Hudson complex	WR		Cusson *et al.* (2007), OBIS
Praxillella affinis (M. Sars in G.O. Sars, 1872)	x			Frobisher Bay	WR		Cusson *et al.* (2007), SLB
Praxillella praetermissa (Malmgren, 1865)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Praxillella sp. Verrill, 1881	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Berkeley and Berkeley (1943), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Prionospio cirrifera Wirén, 1883	x			Frobisher Bay	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Prionospio sp. Malmgren, 1867	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey et al 1979, Wacasey et al 1980, Atkinson and Wacasey 1989a, Cusson et al 2007, SLB
Prionospio steenstrupi Malmgren, 1867		x	x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS
Procerea sp.		x		Hudson complex	WR		Cusson *et al.* (2007), OBIS
Pygospio elegans Claparède, 1863		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Rhodine sp. Malmgren, 1865			x	Hudson complex	WR		Wacasey *et al.* (1976), Conover and Stewart (1978), Cusson *et al.* (2007), OBIS, SLB
Sabellides octocirrata (M. Sars, 1835)	x			Frobisher Bay	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Scalibregma inflatum Rathke, 1843	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Schistomeringos caeca (Webster & Benedict, 1887)		x	x	Hudson complex	WR		SLB, ArcOD
Scoletoma cf. fragilis (O.F. Müller, 1776)	x		x	Hudson Bay	SR (Iq) / WR (DB)	ISE (Iq)	Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS, SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Scoloplos armiger group Blainville, 1828	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Scoloplos sp. Blainville, 1828	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Spio filicornis (Müller, 1776)	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Spio sp. Fabricius, 1785	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Spiophanes sp. Grube, 1860	x			Davis Strait	SR	ISE	Cusson *et al.* (2007), OBIS
Spirorbis sp. Daudin, 1800			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Streptospinigera niuqtuut Olivier, San Martin & Archambault, 2013			x	Canadian High Arctic and North Atlantic coast of United States. Also in western Sweden	AOR	ISE	Olivier *et al.* (2013)
Syllides sp. Örsted, 1845	x	x		Southern Labrador, Barents Sea, Russian Arctic. Arctic and subarctic region	CCD	ISE	Ramos *et al.* (2010), OBIS, GBFI
Syllis sp. Lamarck, 1818			x	Hudson complex	WR		Smithsonian, OBIS, SLB
Terebellides sp. Sars, 1835			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Terebellides stroemii Sars, 1835		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Tharyx sp Webster & Benedict, 1887			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007)
Thelepus cincinnatus (Fabricius, 1780)	x			Frobisher Bay	WR		Cusson *et al.* (2007), OBIS, SLB
Travisia forbesii Johnston, 1840	x		x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Samuelson (2001), OBIS, SLB
Arthropoda - Malacostraca							
Akanthophoreus gracilis (Krøyer, 1842)	x			Hudson complex	SR	ISE	Cusson *et al.* (2007), ArcOD
Ampelisca sp. Krøyer, 1842	x			Frobisher Bay	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Anonyx nugax (Phipps, 1774)	x	x		Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Atkinson and Wacasey (1989b), OBIS, SLB
Argis dentata (Rathbun, 1902)			x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Caprella sp. Lamarck, 1801			x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Corophium sp Latreille, 1806			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Crassicorophium cf crassicorne (Bruzelius, 1859)			x	Hudson complex	WR		Conover and Stewart (1978), Cusson *et al.* (2007), SLB
Diastylis rathkei (Krøyer, 1841)		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Diastylis sp. Say, 1818		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007),

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
							SLB
Ektonodiastylis robusta Gerken, Watling & Klitgaard, 2000			x	Hudson complex	WR		SLB
Eugerda tenuimana (Sars G.O., 1868)			x	Hudson complex	WR		SLB
Gammarus cf. oceanicus Segerstråle, 1947		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), OBIS, SLB
Gammarus setosus Dementieva, 1931	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Gammarus sp. Fabricius, 1775	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Guernea (Prinassus) *nordenskioldi* (Hansen, 1888)			x	Hudson complex	WR		OBIS, SLB, ArcOD
Guernea sp. Chevreux, 1887			x	Hudson complex	WR		OBIS, SLB
Hardametopa carinata (Hansen, 1887)		x	x	Hudson complex	WR		OBIS
Harpinia propinqua Sars, 1891	x			Frobisher Bay	WR		SLB, ArcOD
Lamprops fuscatus Sars, 1865	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Monoculodes borealis Boeck, 1871	x			Frobisher Bay	WR		Cusson *et al.* (2007), SLB
Monoculodes schneideri Sars, 1895			x	White Sea and Arctic Ocean, Beaufort Sea, Gulf of St Lawrence and Newfoundland	WD	ISE	Stebbing (1906), Castillo (1976), Kennedy (1985), OBIS

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Monoculodes sp. Stimpson, 1853			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Monoculopsis longicornis (Boeck, 1871)	x			Frobisher Bay	WR		Cusson *et al.* (2007), SLB
Monoporeia affinis (Lindström, 1855)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Monoporeia sp. Bousfield, 1989			x	Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Nebalia bipes (Fabricius, 1780)	x			Frobisher Bay	WR		Ellis (1957), Ellis (1960), Cusson *et al.* (2007), OBIS, SLB
Oediceros borealis (Boeck, 1871)	x			Frobisher Bay	WR		Cusson *et al.* (2007), SLB
Oediceros saginatus Krøyer, 1842	x			Frobisher Bay	WR		Atkinson and Wacasey (1989b), OBIS
Onisimus litoralis group (Krøyer, 1845)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Onisimus sextoni group Chevreux, 1926			x	Arctic distribution, European waters		Cr	Lowry and Stoddart (1993), Vader *et al.* (2005)
Orchomenella sp. Sars, 1890			x	Hudson complex	WR		OBIS
Paroediceros lynceus (Sars, 1858)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Photis sp. Krøyer, 1842	x			Frobisher Bay	WR		Wacasey (1979), Cusson *et al.* (2007)
Phoxocephalus holbolli (Krøyer, 1842)	x			Frobisher Bay	WR		Cusson *et al.* (2007), SLB
Pontoporeia femorata Krøyer, 1842	x		x	Baffin Frobisher Bay - Hudson complex	WR		Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Protomedeia cf grandimana Brüggen, 1906			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Protomedeia fasciata Krøyer, 1842	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Cusson *et al.* (2007), OBIS, SLB
Protomedeia sp. Krøyer, 1842	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Saduria sabini (Krøyer, 1849)	x			Frobisher Bay	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Arthropoda - Maxillopoda							
Balanus crenatus Bruguière, 1789		x	x	Hudson complex	WR		Ellis (1957), Atkinson and Wacasey (1989b), Lawrence and Baker (1995), Cusson *et al.* (2007), MacDonald *et al.* (2010), OBIS, SLB
Arthropoda - Ostracoda							
Philomedes sp. Liljeborg, 1853	x			Frobisher Bay	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Robertsonites sp. Swain, 1963		x	x	Hudson complex	WR		OBIS, ArcOD
Sarsicytheridea sp.	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		OBIS, ArcOD
Brachiopoda - Rhynchonellata							
Hemithiris psittacea (Gmelin, 1790)		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Bryozoa - Gymnolaemata							
Alcyonidium sp. J.V.F.Lamouroux, 1813	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Callopora sp. Gray, 1848			x	Hudson complex	WR		Osburn (1932), Powell (1968)
Cauloramphus intermedius Kluge, 1962		x		Hudson complex	WR		Kluge (1975)
Cellepora sp. Linnaeus, 1767			x	Hudson complex	WR		Osburn (1932), Powell (1968)
Celleporella hyalina (Linnaeus, 1767)		x	x	Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007), Smithsonian
Einhornia arctica (Borg, 1931)	x			Barents Sea, West Greenland. North America and the Archipelago of Canadian Islands.	CCD	ISE	Kluge (1975)
Escharoides sp. Milne Edwards, 1836			x	Hudson complex	WR		Powell (1968)
Eucratea loricata (Linnaeus, 1758)		x		Hudson Bay	SR (Iq) / WR (Ch)	ISE (Iq)	Atkinson and Wacasey (1989b), Baker (1989), Smithsonian
Harmeria scutulata (Busk, 1855)			x	Hudson complex	WR		Osburn (1932), Kluge (1975)
Lichenopora crassiuscula Smitt, 1867	x			Barents Sea, West Greenland, Archipelago of Canadian Island, Arctic.	CCD	ISE	Kluge (1975)
Myriapora sp. de Blainville, 1830			x	Arctic distribution, European Arctic	CCD	ISE	Kluge (1975), OBIS, SLB
Porella sp. Gray, 1848		x		Hudson complex	WR		Cusson *et al.* (2007)
Rhamphostomella sp. van Lorenz, 1886			x	Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007)
Schizoporella crustacea (Smitt, 1868)			x	Arctic distribution, European Arctic, West Greenland, Davis Strait	CCD	ISE	Kluge (1975), OBIS
Schizoporella sp. Hincks, 1877			x	Hudson complex	WR		Osburn (1932), Powell (1968)
Tegella arctica (d'Orbigny, 1853)			x	Hudson complex	WR		Powell (1968)
Tubulipora cf. flabellaris (O. Fabricius, 1780)	x			Hudson Strait	SR	ISE	Osburn (1932)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Cephalorhyncha - Priapulida							
*Halicryptus spinulos*us von Siebold, 1849		x		Hudson complex	WR		OBIS, SLB, ArcOD
Priapulus caudatus Lamarck, 1816			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Chordata - Ascidiacea							
Boltenia echinata (Linnaeus, 1767)		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Smithsonian, OBIS, SLB
Dendrodoa sp. MacLeay, 1824		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Smithsonian
Heterostigma sp. Ärnbäck-Christie-Linde, 1924			x	Norway, Arctic distribution		Cr	Van Name (1945), OBIS
Molgula griffithsii (MacLeay, 1825)		x		Hudson complex	WR		Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Cnidaria - Hydrozoa							
Campanularia sp. Lamarck, 1816			x	Hudson complex	WR		Baker *et al.* (1994), Atkinson and Wacasey (1989b)
Campanulina pumila (Clark, 1875)		x		Hudson complex	WR		SLB, ArcOD
Filellum serpens (Hassall, 1848)			x	Hudson complex	WR		SLB, ArcOD

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Lafoea sp. Lamouroux, 1821			x	Hudson complex	WR		Smithsonian, SLB
Lafoeina maxima Levinsen, 1893		x		Hudson complex	WR		Atkinson and Wacasey (1989b)
Opercularella lacerata (Johnston, 1847)		x		Hudson complex	WR		SLB, ArcOD
Sertularia sp. Linnaeus, 1758	x			Hudson Bay	SR	ISE	Baker (1989)
Echinodermata - Ophiuroidea							
Amphiura c.f. sundevalli Forbes, 1843	x			Frobisher Bay	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Ophiopholis aculeata (Linnaeus, 1767)		x		Hudson complex	WR		OBIS, SLB, ArcOD
Ophiura robusta (Ayres, 1854)		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Ophiura sp. Lamarck, 1801	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Stegophiura nodosa (Lütken, 1855)	x			Frobisher Bay	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Mollusca - Bivalvia							

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Astarte elliptica complexe (Brown, 1827)	x		x	North Baffin Island / West Greenland Shelf	SR	ISE	Ellis (1957), OBIS
Astarte montagui group (Dillwyn, 1817)			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Astarte sp. J. de C. Sowerby, 1816			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
*Axinopsida orbiculata (*Sars G. O., 1878)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Axinopsida sp Keen & Chavan in Chavan, 1951			x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Axinulus sp. Verrill & Bush, 1898			x	North Atlantic, Arctic oceans, Mediterranean, Beaufort Sea and Alaska	WD	ISE	Bernard (1979), OBIS
Ciliatocardium ciliatum (Fabricius, 1780)			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Cyrtodaria kurriana Dunker, 1861	x			Hudson Bay	SR	ISE	Bernard (1979), SLB
Ennucula tenuis (Montagu, 1808)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Hiatella arctica (Linnaeus, 1767)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Liocyma fluctuosa (Gould, 1841)	x			Frobisher Bay	WR		Cusson *et al.* (2007), OBIS

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Closest region for previous records	Category	Origin	Reference
Macoma balthica (Linnaeus, 1758)		x		Hudson complex	WR		Cusson *et al.* (2007), SLB
Macoma sp Leach, 1819			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Macoma calcarea (Gmelin, 1791)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Musculus discors (Linnaeus, 1767)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mya pseudoarenaria Schlesch, 1931		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Mya sp. Linnaeus, 1758	x		x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Ellis (1960), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mya truncata Linnaeus, 1758	x		x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Ellis (1960), Aitken and Gilbert (1986), Aitken *et al.* (1988), Cusson *et al.* (2007), OBIS, SLB
Mytilus sp. Linnaeus, 1758		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS

APPENDIX III: GENUS AND SPECIES IN CORE SAMPLES (STEENSBY INLET) AND IN QUADRAT SAMPLES (CHURCHILL, DECEPTION BAY AND STEENSBY INLET)

This appendix compiles information on two sets of data that were not included in the publication on *Aquatic Invasions* (Goldsmit *et al.*, 2014) due to time constrains. Nevertheless, they are presented here since they are data that have been obtained as a result of this thesis. Potential publication of the data is possible, probably as a report analyzing these results. Data obtained is presented in this appendix and includes:

1. Core samples taken in field work during the summer 2012 with the same sampling technique and sampling design as explained in Goldsmit *et al.* (2014), but for Steensby Inlet (Nunavut).

   Located at 70.2° N, Steensby Inlet is situated north of Foxe Basin in Nunavut. This was the proposed port site of one of the largest mining developments to date in the Arctic, the Baffinland Mary River Project. It is estimated that the deposit at Mary River contains approximately 375 million tonnes of reserve with a mine life of 21 years. This major mining development was approved in accordance with terms and conditions by the Nunavut Impact Review Board (http://www.nirb.ca/) and it was proposed to be constructed by 2016. It was estimated that the port would accommodate vessels capable of year-round shipping; approximately 10 to 12 ore carriers that would complete 102 round trips every year. This location was sampled with the premise that it was important to study the area before the mine established and started operating, setting groundwork, precedents and a baseline of benthic biota for the region.

   Presently, the mine is at an Early Revenue Phase, which is expected to mine 3.5 Metric Tones *per annum* (Mtpa) of iron ore, transported by trucks to Milne Port and shipped to markets from Milne Port during the open water season. As global markets improve for the prices of iron ore, the Company intends to proceed with the construction and operation of the larger Approved Project which includes the construction and operation of the year around port facilities on Steensby Inlet (http://www.baffinland.com/the-project/location-and-project-history/?lang=en).

2. Quadrat samples were taken in the field work during summers 2011 and 2012 with the same sampling design as explained in Goldsmit *et al.* (2014). These samples were taken in the ports of Churchill, Deception Bay and Steensby Inlet.

   Quadrats of 50 cm^2 were randomly placed at the same zones and elevations where the core samples were taken. Surface material along with any visible organism to a depth of approximately 10-15 cm were collected in a 500 µm mesh bag for sorting and cleaning in the field prior to preservation.

   These results were used as part of an internship of Elliot Dreujou. He finished his Master's Degree in Science of the Universe, Environment and Ecology, in the specialty of Oceanography and Marine Environment at the University of Pierre et Marie Curie (France).

1. List of all genus and species identified in alphabetic order in the port of **Steensby Inlet 2012 with core samples**. Authors, ports where they were found, closest region for previous records, category of distribution pattern, comments about the probable origin and references are reported. Category of distribution pattern: Within Region (WR), Surrounding Region (SR), Arctic Outside Region (AOR), Circumpolar-Circumboreal Distribution (CCD), Wider Distribution including Arctic region (WD). Origin: Increased Survey Effort (ISE), Cryptogenic (Cr). References: Ocean Biogeographic Information System (OBIS), Sea Life Base (SLB), Global Biodiversity Information Systems (GBIF), National Museum of Natural History (Smithsonian)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Annelida - Polychaeta								
Ampharete baltica Eliason, 1955				x	Hudson complex	WR		Pocklington (1989)
Ampharete sibirica Wirén, 1883			x	x	Hudson complex	WR		Wacasey *et al.* (1976), Atkinson and Wacasey (1989c)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Aphelochaeta sp. Blake, 1991			x	x	West Greenland, North Sea, Temperate North America, Laptev Sea (Arctic)	WD	ISE	Blake (1991), OBIS, ArcOD, GBIF
Aricidea nolani Webster & Benedict, 1887	x		x	x	Frobisher Bay	WR		Pocklington (1989), OBIS
Aricidea sp. Webster, 1879	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Capitella sp. Blainville, 1828	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), OBIS, SLB
Chaetozone sp. Malmgren, 1867	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), OBIS
Circeis spirillum (Linnaeus, 1758)			x	x	Hudson complex	WR		Pocklington (1989), OBIS
Cistenides granulata (Linnaeus, 1767)		x	x	x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Cistenides sp Malmgren, 1866				x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Clymenura polaris (Théel, 1879)				x	Hudson complex	WR		Wesenberg-Lund (1950), Curtis (1972), Wacasey *et al.* (1976), OBIS, SLB
Cossura sp. Webster & Benedict, 1887			x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Diplocirrus sp Haase, 1915				x	Hudson complex	WR		Wacasey *et a.l* (1976), OBIS, SLB
Dipolydora caulleryi (Mesnil, 1897)		x	x	x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Dipolydora quadrilobata (Jacobi, 1883)	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Cusson *et al.* (2007), Smithsonian, SLB
Dipolydora socialis group (Schmarda, 1861)			x	x	Barents Sea, Atlantic and Pacific ocean		Cr	Dahle *et al.* (1998), OBIS, SLB, ArcOD

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Eteone sp. Savigny, 1818	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Euchone incolor Hartman, 1965				x	Hudson complex	WR		Stewart *et al.* (1985), Pocklington (1989)
Euchone sp. Malmgren, 1866	x		x	x	Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Eulalia viridis (Linnaeus, 1767)				x	Hudson complex	WR		Wesenberg-Lund (1950), Pocklington (1989)
Exogone (Exogone) nadina Örsted, 1845			x	x	Hudson complex	WR		Wacasey (1979), OBIS, ArcOD
Exogone (Parexogone) longicirris (Webster & Benedict, 1887)	x	x	x	x	Hudson complex	WR		Pocklington (1989)
Gattyana cirrhosa (Pallas, 1766)		x		x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Harmothoe imbricata (Linnaeus, 1767)		x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Harmothoe sp. Kinberg, 1856	x	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Lanassa venusta (Malm, 1874)				x	Hudson complex	WR		Wacasey *et al.* (1976), Wacasey (1979), Wacasey *et al.* (1980), OBIS, SLB
Laonome kroyeri Malmgren, 1866			x		Hudson complex	WR		SLB, ArcOD
Laphania boecki Malmgren, 1866	x			x	Frobisher Bay	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), SLB
Levinsenia gracilis (Tauber, 1879)				x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), OBIS

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Maldane sp Grube, 1860				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS
Melinna elisabethae McIntosh, 1918				x	Hudson complex	WR		Blake and Dean (1973), Pocklington (1989)
Micronephthys minuta (Théel, 1879)				x	Hudson complex	WR		Wacasey *et al.* (1976), Wacasey (1979), Wacasey *et al.* (1980), OBIS, SLB
Microphthalmus sp. Mecznikow, 1865	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), SLB
Nephtys ciliata (Müller, 1788)	x	x		x	Baffin Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Samuelson (2001), Cusson *et al.* (2007), OBIS, SLB
Nephtys incisa Malmgren, 1865		x		x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Nephtys longosetosa Örsted, 1842				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey *et al.* (1980), OBIS, SLB
Nephtys paradoxa Malm, 1874				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB
Nephtys pente Rainer, 1984				x	West Grenland shelf, Northern European Seas, Barents Sea, Baltic Sea, Arctic	CCD	ISE	Rainer (1984), OBIS
Nephtys sp Cuvier, 1817				x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Nereimyra sp. Blainville, 1828			x	x	Hudson complex	WR		Wacasey *et al* (1976), Atkinson and Wacasey (1989c), OBIS, SLB
Nereis zonata Malmgren, 1867				x	Hudson complex	WR		Conover and Stewart (1978), Atkinson and Wacasey (1989b), OBIS, SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Ophryotrocha sp. Claparède & Mecznikow, 1869		x	x	x	Hudson complex	WR		Berkeley and Berkeley (1943), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Paraonides nordica Strelzov, 1968	x	x	x	x	West Greenland Shelf / Barents Sea		Cr	Strelzov (1979), OBIS
Petaloproctus tenuis (Théel, 1879)				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB
Pholoe longa (O.F. Müller, 1776)		x	x	x	Southern Labrador, High Eastern Arctic, West Greenland Shelf, Beaufort Sea	AOR	ISE	Pocklington (1989), Pettibone (1992), OBIS
Pholoe sp. Johnston, 1839	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Phyllodoce groenlandica Örsted, 1842			x	x	Hudson complex	WR		Cusson et al 2007, OBIS
Phyllodoce mucosa Örsted, 1843				x	Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), OBIS, SLB
Polydora sp Bosc, 1802				x	Hudson complex	WR		Cusson *et al.* (2007), OBIS
Praxillella praetermissa (Malmgren, 1865)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Praxillella sp. Verrill, 1881	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Berkeley and Berkeley (1943), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Prionospio sp. Malmgren, 1867	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Pseudoscalibregma parvum (Hansen, 1879)				x	Hudson complex	WR		OBIS
Pygospio elegans Claparède, 1863		x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Scalibregma inflatum Rathke, 1843	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Scalibregma sp Rathke, 1843				x	Hudson complex	WR		
Schistomeringos caeca (Webster & Benedict, 1887)		x	x		Hudson complex	WR		SLB, ArcOD
Scolelepis sp Blainville, 1828				x	Hudson complex	WR		OBIS
Scoletoma cf. fragilis (O.F. Müller, 1776)	x		x		Hudson Bay	SR (Iq) / WR (DB)	ISE (Iq)	Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Scoloplos armiger group Blainville, 1828	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS, SLB
Sphaerodoropsis minuta (Webster & Benedict, 1887)				x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), OBIS, SLB
Spio sp. Fabricius, 1785	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Syllides sp. Örsted, 1845	x	x	x	x	Southern Labrador, Barents Sea, Russian Arctic. Arctic and subarctic region	CCD	ISE	Ramos *et al.* (2010), OBIS, GBFI

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Terebellides stroemii Sars, 1835		x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Travisia forbesii Johnston, 1840	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Samuelson (2001), OBIS, SLB
Arthropoda - Malacostraca								
Akanthophoreus gracilis (Krøyer, 1842)	x			x	Hudson complex	SR (Iq) / WR (SI)	ISE	Cusson *et al.* (2007), ArcOD
Caprella septentrionalis Krøyer, 1838				x	Hudson complex	WR		Wacasey (1979), OBIS, SLB
Ektonodiastylis robusta Gerken, Watling & Klitgaard, 2000			x	x	Hudson complex	WR		SLB
Eualus fabricii (Krøyer, 1841)				x	Hudson complex	WR		OBIS
Eugerda tenuimana (Sars G.O., 1868)			x	x	Hudson complex	WR		SLB
Gammarus cf. oceanicus Segerstråle, 1947		x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), OBIS, SLB
Gammarus setosus Dementieva, 1931	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Guernea (Prinassus) *nordenskioldi* (Hansen, 1888)			x	x	Hudson complex	WR		OBIS, SLB, ArcOD
Hardametopa carinata (Hansen, 1887)		x	x	x	Hudson complex	WR		OBIS
Hardametopa nasuta (Boeck, 1871)				x	Hudson complex	WR		Wacasey (1979), OBIS, SLB
Ischyrocerus anguipes Krøyer, 1838				x	Hudson complex	WR		Wacasey *et al.* (1976), Wacasey (1979), Atkinson and Wacasey (1989b), OBIS, SLB
Lamprops fuscatus Sars, 1865	x	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Lamprops sp G.O. Sars, 1863				x	Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Metopa sp Boeck, 1871				x	Hudson complex	WR		Wacasey *et al.* (1976), Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB
Monoculodes sp. Stimpson, 1853			x	x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Monoporeia affinis (Lindström, 1855)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Munna fabricii Krøyer, 1846				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB
Onisimus litoralis group (Krøyer, 1845)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Pagurus pubescens Krøyer, 1838				x	Hudson complex	WR		OBIS
Pagurus sp Fabricius, 1775				x	Hudson complex	WR		OBIS
Paroediceros lynceus (Sars, 1858)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Protomedeia fasciata Krøyer, 1842	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Cusson *et al.* (2007), OBIS, SLB
Saduria sabini (Krøyer, 1849)	x			x	Frobisher Bay	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Sclerocrangon boreas (Phipps, 1774)				x	Hudson complex	WR		OBIS
Arthropoda - Maxillopoda								

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Balanus crenatus Bruguière, 1789		x	x	x	Hudson complex	WR		Ellis (1957), Atkinson and Wacasey (1989b), Lawrence and Baker (1995), Cusson *et al.* (2007), MacDonald *et al.* (2010), OBIS, SLB
Arthropoda - Ostracoda								
Elofsonella sp Pokorny, 1955				x	Hudson complex	WR		OBIS
Philomedes sp. Liljeborg, 1853	x			x	Frobisher Bay	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Sarsicytheridea sp.	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		OBIS, ArcOD
Sclerochilus sp Sars, 1866				x	Hudson complex	WR		Wacasey *et al.* (1980), OBIS
Arthropoda - Pycnogonida								
Nymphon microrhynchum G.O. Sars, 1888				x	Hudson complex	WR		OBIS
Bryozoa - Gymnolaemata								
Celleporella hyalina (Linnaeus, 1767)		x	x	x	Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007), Smithsonian
Cribrilina sp Gray, 1848				x	Hudson complex	WR		Osburn (1932), Powell (1968)
Cribrilina spitzbergensis Norman, 1903				x	Barents, Kara, Bering seas, Weste greenland, White sea, high Arctic species	CCD	ISE	Kluge (1975), OBIS
Crisia sp Lamouroux, 1812				x	Archipelago of Canadian Islands, Arctic species, Gulf of Maine, Northern Seas, White Sea, Barents Sea	CCD	ISE	Kluge (1975), OBIS
Escharella sp. Gray, 1848			x	x	Hudson complex	WR		Powell (1968), OBIS

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Eucratea loricata (Linnaeus, 1758)		x		x	Hudson Bay	SR (Iq) / WR (Ch)	ISE (Iq)	Atkinson and Wacasey (1989b), Baker (1989), Smithsonian
Rhamphostomella sp van Lorenz, 1886			x	x	Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007)
Scrupocellaria minor Kluge, 1915				x	Barents and Easte Siberian seas, Western Greenland, White sea	CCD	ISE	Kluge (1975), OBIS
Securiflustra securifrons (Pallas, 1766)				x	Hudson complex	WR		Osburn (1932), Powell (1968)
Tegella arctica (d'Orbigny, 1853)			x	x	Hudson complex	WR		Powell (1968)
Tegella sp. Levinsen, 1909			x	x	Hudson complex	WR		Powell (1968)
Chordata - Ascidiacea								
Boltenia echinata (Linnaeus, 1767)		x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Smithsonian, OBIS, SLB
Heterostigma sp. Ärnbäck-Christie-Linde, 1924			x		Norway, Arctic distribution		Cr	(Van Name, 1945), OBIS
Molgula griffithsii (MacLeay, 1825)		x			Hudson complex	WR		Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Cnidaria - Hydrozoa								
Filellum serpens (Hassall, 1848)			x	x	Hudson complex	WR		SLB, ArcOD
Halecium sp Oken, 1815				x	Beaufort Sea, Barents Sea, White Sea, Gulf of St.Lawrence, Northern European Seas, Greenland, Norway, Iceland, Alaska, central Arctic ocean	WD	ISE	Naumov (1969), Wacasey (1975), OBIS
Lafoea sp. Lamouroux, 1821			x	x	Hudson complex	WR		Smithsonian, SLB
Tubularia sp Linnaeus, 1758				x	Hudson complex	WR		Naumov (1969)

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Echinodermata - Asteroidea								
Asterias sp Linnaeus, 1758				x	Hudson complex	WR		SLB
Echinodermata - Holothuroidea								
Myriotrochus sp Steenstrup, 1851				x	Hudson complex	WR		OBIS
Echinodermata - Ophiuroidea								
Stegophiura nodosa (Lütken, 1855)	x			x	Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Mollusca - Bivalvia								
Astarte borealis complex (Schumacher, 1817)				x	Hudson complex	WR		Wacasey *et al.* (1976), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), OBIS, SLB
Astarte sp. J. de C. Sowerby, 1816			x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Ennucula delphinodonta (Mighels & C. B. Adams, 1842)				x	Hudson complex	WR		SLB
Ennucula tenuis (Montagu, 1808)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Hiatella arctica (Linnaeus, 1767)	x	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Macoma sp Leach, 1819			x	x	Hudson complex	WR		Cusson *et al.* (2007), SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Macoma calcarea (Gmelin, 1791)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Montacuta sp Turton, 1822				x	Hudson complex	WR		SLB
Musculus discors (Linnaeus, 1767)	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mya sp. Linnaeus, 1758	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Ellis (1960), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mya truncata Linnaeus, 1758	x		x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Ellis (1960), Aitken and Gilbert (1986), Aitken *et al.* (1988), Cusson *et al.* (2007), OBIS, SLB
Mytilus sp. Linnaeus, 1758		x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Nuculana minuta (O. F. Müller, 1776)				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Atkinson and Wacasey (1989b), SLB
Portlandia sp Mörch, 1857				x	Hudson complex	WR		Wacasey *et al.* (1976), Atkinson and Wacasey (1989b)
Serripes groenlandicus (Mohr, 1786)				x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), OBIS, SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Thyasira cf gouldi (Philippi, 1845)			x	x	Hudson complex	WR		Wacasey *et al.* (1976), Conover and Stewart (1978), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mollusca - Gastropoda								
Ariadnaria borealis (Broderip & G. B. Sowerby I, 1829)				x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), OBIS, SLB
Lepeta caeca (O. F. Müller, 1776)				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB
Margarites helicinus (Phipps, 1774)	x			x	Frobisher Bay	WR		Conover and Stewart (1978), Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Margarites sp. Gray, 1847			x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Propebela harpularia (Couthouy, 1838)				x	Hudson complex	WR		McPherson (1971)
Propebela sp Iredale, 1918				x	Hudson complex	WR		OBIS
Puncturella noachina (Linnaeus, 1771)			x		Hudson complex	WR		Cusson *et al.* (2007), SLB
*Retusa obtusa (*Montagu, 1803)			x	x	Hudson complex	WR		Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Tachyrhynchus erosus (Couthouy, 1838)	x			x	Frobisher Bay	WR		Wacasey (1979), Cusson *et al.* (2007), SLB

Taxa	Iqaluit 2011	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Tachyrhynchus reticulatus (Mighels & Adams, 1842)				x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Atkinson and Wacasey (1989c), OBIS, SLB
Mollusca - Polyplacophora								
Tonicella rubra (Linnaeus, 1767)		x		x	Baffin Bay	SR	ISE	Thomson *et al.* (1986)

2. List of all genus and species identified in alphabetic order in the ports of **Churchill (2011), Decpetion Bay (2012) and Steensby Inlet (2012) with quadrat samples**. Authors, ports where they were found, closest region for previous records, category of distribution pattern, comments about the probable origin and references are reported. Category of distribution pattern: Within Region (WR), Surrounding Region (SR), Arctic Outside Region (AOR), Circumpolar-Circumboreal Distribution (CCD), Wider Distribution including Arctic region (WD). Origin: Increased Survey Effort (ISE), Cryptogenic (Cr). References: Ocean Biogeographic Information System (OBIS), Sea Life Base (SLB), Global Biodiversity Information Systems (GBIF), National Museum of Natural History (Smithsonian)

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Annelida - Polychaeta							
Ampharete sibirica Wirén, 1883		x		Hudson complex	WR		Pocklington (1989)
Ampharete sp. Malmgren, 1866	x			Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Aricidea nolani Webster & Benedict, 1887		x		Frobisher Bay, Hudson Complex	WR		Pocklington (1989), OBIS
Bipalponephtys neotena (Noyes, 1980)		x		Beaufort Sea, White Sea, Gulf St. Lawrence, Bay of Fundy	WD	ISE	Appy *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), MacDonald *et al.* (2010), OBIS
Chaetozone sp. Malmgren, 1867		x		Baffin Frobisher Bay	WR		Wacasey (1979), OBIS

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
				- Hudson complex			
Cirratulus sp. Lamarck, 1818		x		Beaufort Sea, Hudson Complex, Northern Labrador	WR		Berkeley and Berkeley (1943), Grainger (1954), Wacasey *et al.* (1975), Wacasey *et al.* (1980), Atkinson and Wacasey (1989a)
Cistenides granulata (Linnaeus, 1767)	x	x	x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Eteone sp. Savigny, 1818	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007)Cusson et al 2007, OBIS
Glycera capitata Örsted, 1843	x			Hudson complex	WR		OBIS, SLB, ArcOD
Harmothoe extenuata (Grube, 1840)			x	Beaufort Sea, Hudson Complex, Buffin Frobisher Bay	WR		Wacasey *et al.* (1975), Conover and Stewart (1978), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), , Wacasey (1979), Wacasey *et al.* (1980),
Harmothoe imbricata (Linnaeus, 1767)			x	Baffin Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Harmothoe sp. Kinberg, 1856	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Laonome sp. Malmgren, 1866			x	Hudson complex	WR		SLB, ArcOD
Laphania boecki Malmgren, 1866			x	Frobisher Bay, Hudson Complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), SLB
Nephtys longosetosa Örsted, 1842			x	Hudson complex	WR		Conover and Stewart (1978), Wacasey *et al.* (1980), OBIS, SLB

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Nephtys sp Cuvier, 1817	x		x	Hudson complex	WR		Cusson *et al.* (2007), OBIS, SLB
Nereimyra sp. Blainville, 1828			x	Hudson complex	WR		Wacasey *et al.* (1976), Atkinson and Wacasey (1989c), OBIS, SLB
Nereis pelagica Linnaeus, 1758	x	x		Beaufort Sea, Hudson Complex, Northern Labrador	WR		Atkinson and Wacasey (1989b), Berkeley and Berkeley (1943), Grainger (1954), Jirkov and Leontovich (2012), Smithsonian
Nereis zonata Malmgren, 1867			x	Hudson complex	WR		Conover and Stewart (1978), Atkinson and Wacasey (1989b), OBIS, SLB
Nicolea zostericola Örsted, 1844			x	Hudson Complex, Northern Labrador	WR		Wacasey *et al.* (1976), Atkinson and Wacasey (1989c), Wacasey (1979), Berkeley and Berkeley (1943), Grainger (1954)
Ophelia borealis Quatrefages, 1866	x			North Sea, Barents Sea, South European Atlanrtic Shelf		Cr	OBIS, SLB
Ophelia limacina (Rathke, 1843)	x	x		Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Samuelson (2001), Cusson *et al.* (2007), OBIS, SLB
Owenia borealis Koh, Bhaud & Jirkov, 2003		x		North Atlantic, Norwegian waters, Greenland, Barents Sea		Cr	Koh and Bhaud (2003), Jirkov and Leontovich (2012)
Pholoe longa (O.F. Müller, 1776)	x			Southern Labrador, High Eastern Arctic, West Greenland Shelf, Beaufort Sea	AOR	ISE	Pocklington (1989), Pettibone (1992), OBIS
Pholoe sp. Johnston, 1839	x			Baffin Frobisher Bay - Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Phyllodoce groenlandica Örsted, 1842		x		Hudson complex	WR		Cusson *et al.* (2007), OBIS
Praxillella praetermissa (Malmgren, 1865)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Praxillella sp. Verrill, 1881			x	Baffin Frobisher Bay - Hudson complex	WR		Berkeley and Berkeley (1943), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Prionospio steenstrupi Malmgren, 1867		x		Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS
Scalibregma inflatum Rathke, 1843	x			Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Scoletoma cf. fragilis (O.F. Müller, 1776)	x			Hudson Bay	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Cusson *et al.* (2007), OBIS, SLB
Scoloplos armiger group Blainville, 1828	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Sphaerodorum gracilis (Rathke, 1843)			x	Beaufort Sea, Hudson Complex, Northern Labrador	WR		Grainger (1954), Wacasey *et al*. (1975), Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Smithsonian
Spio sp.	x	x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Arthropoda - Malacostraca							
Anonyx nugax (Phipps, 1774)	x			Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Atkinson and Wacasey (1989b), OBIS, SLB
Atylus carinatus(Fabricius, 1793)	x		x	Beaufort Sea, Hudson Complex, Baffin Frobisher Bay, Lancaster Sound, High Arctic Archipelago	WR		Wacasey *et al.* (1975), Thomson *et al.* (1986), Smithsonian
Caprella septentrionalis Krøyer, 1838			x	Hudson complex	WR		Wacasey (1979), OBIS, SLB
Diastylis rathkei (Krøyer, 1841)	x			Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB
Eualus fabricii (Krøyer, 1841)			x	Hudson complex	WR		OBIS
Gammarus cf. oceanicus Segerstråle, 1947	x	x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), OBIS, SLB
Gammarus setosus Dementieva, 1931	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Ischyrocerus anguipes Krøyer, 1838			x	Hudson complex	WR		Wacasey *et al* (1976), Wacasey (1979), Atkinson and Wacasey (1989b), OBIS, SLB

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Lebbeus polaris (Sabine, 1824)			x	Beaufort Sea, Hudson Complex, Baffin Frobisher Bay, Lancaster Sound, High Arctic Archipelago	WR		Thomson *et al.* (1986)
Metopa glacialis (Krøyer, 1842)			x	Hudson Complex, Northern Labrador	WR		Wacasey (1979), Wacasey *et al.* (1980)
Monoculodes sp. Stimpson, 1853			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Monoporeia affinis (Lindström, 1855)		x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Onisimus litoralis group (Krøyer, 1845)		x	x	Baffin Frobisher Bay - Hudson complex	WR		Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Pagurus pubescens Krøyer, 1838			x	Hudson complex	WR		OBIS
Paroediceros lynceus (Sars, 1858)			x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Pleustes (Pleustes) panoplus (Krøyer, 1838)			x	Beaufort Sea, Hudson Complex, Northern Labrador	WR		Wacasey (1979)
Saduria sabini (Krøyer, 1849)			x	Frobisher Bay, Hudson Complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Arthropoda - Maxilopoda							
Balanus crenatus Bruguière, 1789	x		x	Hudson complex	WR		Ellis (1957), Atkinson and Wacasey (1989b), Lawrence and Baker (1995), Cusson *et al.* (2007), MacDonald *et al.* (2010), OBIS, SLB
Arthropoda - Ostracoda							

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Philomedes sp. Liljeborg, 1853			x	Frobisher Bay, Hudson Complex	WR		Wacasey (1979), Wacasey *et al.* (1980), Cusson *et al.* (2007)
Brachiopoda - Rhynchonellata							
Hemithiris psittacea (Gmelin, 1790)	x			Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS
Bryozoa - Gymnolaemata							
Alcyonidium sp. J.V.F.Lamouroux, 1813	x			Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Aquiloniella paenulata (Norman, 1903)			x	Hudson Complex	WR		Osburn (1932), OBIS
Celleporella hyalina (Linnaeus, 1767)	x	x		Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007), Smithsonian
Einhornia arctica (Borg, 1931)	x			Barents Sea, West Greenland. North America and the Archipelago of Canadian Islands.	CCD	ISE	Kluge (1975)
Escharella sp. Gray, 1848			x	Hudson complex	WR		Powell (1968), OBIS
Harmeria scutulata (Busk, 1855)		x	x	Hudson complex	WR		Osburn (1932), Kluge (1975)
Hippoporella hippopus(Smitt, 1868)	x			Chukchi, Bering Sea, Barents Sea. Gulf of Maine	WD	ISE	OBIS
Myriapora sp. de Blainville, 1830	x			Arctic distribution, European Arctic	CCD	ISE	Kluge (1975), OBIS, SLB
*Porella proboscidea*Hincks, 1888		x		Hudson Complex	WR		Osburn (1932)
Porella sp. Gray, 1848	x			Hudson complex	WR		Cusson *et al.* (2007)
Rhamphostomella sp van Lorenz, 1886		x		Hudson complex	WR		Osburn (1932), Powell (1968), Cusson *et al.* (2007)
Schizoporella sp. Hincks, 1877	x	x		Hudson complex	WR		Osburn (1932), Powell (1968)

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Smittina sp. Norman, 1903			x	Hudson complex	WR		Osburn (1932)
Tegella sp. Levinsen, 1909			x	Hudson complex	WR		Powell (1968)
Chordata - Ascidiacea							
Boltenia echinata (Linnaeus, 1767)		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Smithsonian, OBIS, SLB
*Styela rustica*Linnaeus, 1767	x			Beaufort Sea, Hudson Complex, Lancaster Sound, Baffin Frobisher Bay, High Arctic Archipelago	WR		Wacasey *et al.* (1976), Wacasey (1979), Wacasey *et al.* (1980), Thomson *et al.* (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Smithsonian
Cnidaria - Hydrozoa							
Obelia longissima (Pallas, 1766)		x		Hudson Complex	WR		SLB
Echinodermata - Echinoidea							
Strongylocentrotus sp. Brandt, 1835		x	x	Beaufort Sea, Hudson Complex, Northern Labrador, Lancaster Sound, Baffin Frobisher Bay, High Arctic Archipelago	WR		Wacasey et al. 1976, Conover and Stewart (1978), Wacasey (1979), Thomson *et al.* (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989a), Smithsonian
Echinodermata - Holothuroidea							
Cucumaria frondosa (Gunnerus, 1767)			x	Beaufort Sea, Hudson Complex	WR		Atkinson and Wacasey (1989b), Smithonian
Psolus sp. Jaeger, 1833	x	x		Beaufort Sea, Hudson Complex, Northern Labrador, Baffin Frobisher Bay,	WR		Ellis (1960), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Smithsonian
Echinodermata - Ophiuroidea							

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Ophiacantha bidentata (Bruzelius, 1805)			x	Beaufort Sea, Hudson Complex, Northern Labrador, Baffin Frobisher Bay,	WR		Conover and Stewart (1978), Wacasey (1979), Thomson *et al.* (1986), Smithsonian
Ophiopholis aculeata (Linnaeus, 1767)	x			Hudson complex	WR		OBIS, SLB, ArcOD
Ophiopus arcticus Ljungman, 1867			x	Hudson Complex, Bafin Frobisher Bay, Northern Labrador	WR		Wacasey *et al.* (1976), Conover and Stewart (1978), Wacasey (1979), Atkinson and Wacasey (1989c), Smithsonian
Ophiura robusta (Ayres, 1854)	x	x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Ophiura sarsii Lütken, 1855		x		Beaufort Sea, Hudson Complex, Baffin Frobisher Bay, West Greenland Shelf	WR		Ellis (1960), Conover and Stewart (1978), Atkinson and Wacasey (1989b), Smithsonian
Stegophiura nodosa (Lütken, 1855)			x	Frobisher Bay - Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), Smithsonian, OBIS, SLB
Mollusca - Bivalvia							
Astarte sp. J. de C. Sowerby, 1816			x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
*Axinopsida orbiculata (*Sars G. O., 1878)		x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Crenella faba(O. F. Müller, 1776)	x	x	x	Beaufort Sea, Hudson Complex, Baffin Frobisher Bay, Lancaster	WR		Thomson *et al.* (1986), (Aitken & Gilbert, 1986), Atkinson and Wacasey (1989c)

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
				Sound, High Arctic Archipelago			
Hiatella arctica (Linnaeus, 1767)	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Aitken *et al.* (1988), Atkinson and Wacasey (1989b), Cusson *et al.* (2007), OBIS, SLB
Macoma balthica (Linnaeus, 1758)	x			Hudson complex	WR		Cusson *et al.* (2007), SLB
Macoma calcarea (Gmelin, 1791)		x		Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Musculus discors (Linnaeus, 1767)	x		x	Baffin Frobisher Bay - Hudson complex	WR		Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Mya truncata Linnaeus, 1758	x	x	x	Baffin Frobisher Bay - Hudson complex	WR		Ellis (1957), Ellis (1960), Aitken and Gilbert (1986), Aitken *et al.* (1988), Cusson *et al.* (2007), OBIS, SLB
Mytilus sp. Linnaeus, 1758	x	x		Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS
Mollusca - Gastropoda							
Ariadnaria borealis (Broderip & G. B. Sowerby I, 1829)			x	Hudson complex	WR		Wacasey (1979), Wacasey *et al.* (1980), OBIS, SLB
Lepeta caeca (O. F. Müller, 1776)			x	Hudson complex	WR		Conover and Stewart (1978), Wacasey (1979), Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), OBIS, SLB

Taxa	**Churchill 2011**	**Deception Bay 2012**	**Steensby Inlet 2012**	**Closest region for previous records**	**Category**	**Origin**	**Reference**
Littorina sp. Férussac, 1822	x	x		Hudson complex	WR		OBIS, SLB
Margarites cf. costalis (Gould, 1841)		x		Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Margarites groenlandicus (Gmelin, 1791)			x	Hudson Complex, Northern Labrador	WR		Conover and Stewart (1978), Wacasey (1979)
Margarites groenlandicus groenlandicus (Gmelin, 1791)	x		x	Hudson complex	WR		Conover and Stewart (1978), Cusson *et al.* (2007) OBIS, SLB
Margarites cf. groenlandicus umbilicalis Broderip & Sowerby, 1829			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Margarites helicinus (Phipps, 1774)			x	Frobisher Bay, Hudson Complex	WR		Conover and Stewart (1978), Wacasey *et al.* (1980), Aitken and Gilbert (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), OBIS, SLB
Margarites sp. Gray, 1847		x	x	Hudson complex	WR		Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c), Cusson *et al.* (2007), SLB
Margarites sordidus (Hancock, 1846)			x	Gulf of Maine, Chukchi Sea, Barents Sea, Svalbard	WD	ISE	OBIS, SLB
Oenopota sp. Mörch, 1852		x	x	Frobisher Bay, Hudson Complex	WR		Wacasey *et al.* (1980), Atkinson and Wacasey (1989b), Cusson *et al.* (2007)
Puncturella noachina (Linnaeus, 1771)			x	Hudson complex	WR		Cusson *et al.* (2007), SLB
Tachyrhynchus erosus (Couthouy, 1838)			x	Frobisher Bay, Hudson Complex	WR		Wacasey (1979), Cusson *et al.* (2007), SLB
Testudinalia testudinalis (O. F. Müller, 1776)	x	x		Hudson complex	WR		Atkinson and Wacasey (1989b), Cusson *et al.* (2007), SLB

Taxa	Churchill 2011	Deception Bay 2012	Steensby Inlet 2012	Closest region for previous records	Category	Origin	Reference
Velutina velutina (O. F. Müller, 1776)			x	Beaufort Sea, Hudson Complex, Northern Labrador, West Greenland Shelf	WR		Ellis (1960), Wacasey (1979), Wacasey *et al.* (1980)
Mollusca - Polyplacophora							
Tonicella marmorea (O. Fabricius, 1780)		x	x	Beaufort Sea, Hudson Complex, Baffin Frobisher Bay, Lancaster Sound, High Arctic Archipelago	WR		Wacasey (1979), Thomson *et al.* (1986), Atkinson and Wacasey (1989b), Atkinson and Wacasey (1989c),
Tonicella rubra (Linnaeus, 1767)	x			Baffin Bay	SR	ISE	Thomson *et al.* (1986)
Porifera - Calcarea							
Sycon sp. Risso, 1827		x		West Greenland Shelf, Beaufort Sea, Barents Sea, Temperate regions	WD	ISE	OBIS, SLB

CHAPITRE 2
PROJECTION DES HABITATS PRÉSENTS ET FUTURS PROPICES AUX ESPÈCES AQUATIQUES ENVAHISSANTS DANS L'ARCTIQUE CANADIEN

RÉSUMÉ

Il est attendu que l'augmentation de l'activité de navigation dans l'Arctique, résultant du réchauffement climatique global et de l'exploitation accrue des ressources, pourrait accroître le risque d'introduction d'espèces aquatiques envahissantes (EAE) dans cette région. Dans ce contexte, le risque potentiel de futures incursions d'EAE à l'échelle de l'Arctique canadien a été examiné. Les habitats propices ont été prédits pour un sous-ensemble d'EAE présentant une menace élevée dans les conditions environnementales actuelles ainsi que sous les scénarios de changements climatiques futurs. Huit envahisseurs potentiels avec un danger relatif élevé pour l'Arctique canadien ont été identifiés : 1) *Amphibalanus improvisus*, 2) *Botrylloides violaceus*, 3) *Caprella mutica*, 4) *Carcinus maenas*, 5) *Littorina littorea*, 6) *Membranipora membranacea*, 7) *Mya arenaria* et 8) *Paralithodes camtschaticus*. La modélisation des habitats a été effectuée à l'aide de MaxEnt à partir des données d'occurrences natives et non indigènes et à partir des aires environnementales connues à l'échelle mondiale pour ces espèces. Les résultats de la modélisation ont montré que l'habitat est propice sous les conditions environnementales actuelles dans certaines régions de l'Arctique canadien comme le complexe d'Hudson et la mer de Beaufort pour trois des espèces étudiées : *L. littorea*, *M. arenaria* et *P. camtschaticus*. Le caractère propice de l'habitat a été projeté dans des scénarios de changements climatiques pour l'ensemble des espèces modélisées. L'utilisation de ces modèles aidera à comprendre les risques potentiels de futures incursions d'EAE résultant du changement climatique et de la navigation, et ce, à de grandes échelles spatiales. Ces approches aideront à identifier les régions et les espèces à haut risque afin de permettre une

surveillance et des efforts de recherche plus ciblés sur les EAE en réponse au changement climatique.

PROJECTING PRESENT AND FUTURE HABITAT SUITABILITY OF AQUATIC INVASIVE SPECIES IN THE CANADIAN ARCTIC

ABSTRACT

An increase in Arctic shipping activity resulting from global warming and resource exploitation is expected to increase the likelihood of aquatic invasive species (AIS) introductions in the region. In this context, the potential threat of future AIS incursions at a Canadian Arctic regional scale was examined. Habitat suitability was projected for a subset of higher risk AIS under current environmental conditions and future climate change scenarios. Eight potential invaders with relative high risk for the Canadian Arctic were identified: 1) *Amphibalanus improvisus*, 2) *Botrylloides violaceus*, 3) *Caprella mutica*, 4) *Carcinus maenas*, 5) *Littorina littorea*, 6) *Membranipora membranacea*, 7) *Mya arenaria* and 8) *Paralithodes camtschaticus*. Habitat modelling was performed using MaxEnt based on globally known native and non-native occurrence records and environmental ranges for these species. Modelling results showed that the habitat is suitable under current environmental conditions in certain regions of the Canadian Arctic such as the Hudson Complex and Beaufort Sea for three of the species modelled: *L. littorea*, *M. arenaria* and *P. camtschaticus*. Under the future climate change scenario, habitat suitability was projected for the complete suite of species modelled. The utilization of these models will help in understanding potential future AIS incursions as a result of climate change and shipping at large spatial scales. These approaches will aid in the identification of high risk regions and species to allow for more focused AIS monitoring and research efforts in response to climate change.

Key words: Arctic, biological invasions, climate change, MaxEnt, ship-mediated invasive species, species distribution modelling.

The second chapter was co-authored by me, Dr. Kimberly Howland, Dr. Guillem Chust, PhD candidate Ernesto Villarino, Dr. George Liu, Dr. Jennifer V. Lukovich, Dr.

David G. Barber and Dr. Philippe Archambault. It will be submitted in *Polar Biology* journal. As first author, I conceived the research project together with Dr. Howland and Dr. Archambault. I also ran the species distribution modelling with the aid of Dr. Chust and PhD candidate Villarino (an internship on modelling was done in AZTI Technalia, Basque Country, Spain, under the supervision of Dr. Chust). Dr. Liu, Dr. Lukovich and Dr. Barber provided the future projected model layers. Also, as first author, I wrote the manuscript with the input from all other co-authors.

Parts, short and full versions of this work were presented as oral and poster presentations at the following conferences: 1) 48th Canadian Meteorological and Oceanographic Society (CMOS) in Rimouski (Canada) in June 2014; 2) ICES Annual Science Conference in A Coruña (Spain) in September 2014; 3) Québec-Ocean Annual General Meeting in Rivière du Loup (Canada) in November 2014; 4) ASLO Aquatic Science Meeting in Granada (Spain) in February 2015; 5) Association of Polar Early Carrier Scientist (APECS), International Online Conference in March 2015 (*Awarded 2nd best presentation*); 6) Canadian Aquatic Invasive Species Network Annual General Meeting in Halifax (Canada) in April 2015; 7) 83^{e} du Congrès de l'Acfas in Rimouski (Canada) in May 2015, 8) Québec-Ocean Annual General Meeting in Quebec city (Canada) in November 2015, 9) International Conference on Marine Bioinvasions in Sydney (Australia) in January 2016.

INTRODUCTION

Aquatic invasive species (AIS) have become a serious threat to biodiversity over the past century (Cohen & Carlton, 1998; Grosholz, 2002; CAFF, 2013). Most aquatic invaders have been introduced through ballast water and/or hull fouling vectors and are coastal or estuarine in origin (Locke *et al.*, 1993; Ruiz *et al.*, 2000). Most introductions have occurred at lower latitudes where there is the greatest shipping activity (Ruiz *et al.*, 2000). Nevertheless, the Arctic is also likely to receive introductions due to global warming, resource exploitation and the increase in Arctic shipping activity (Smith & Stephenson, 2013; Miller & Ruiz, 2014). All these factors can facilitate the introduction of exotic species to Arctic waters (Niimi, 2004; Ware *et al.*, 2014). The Arctic Ocean covers approximately 10 million km^2, 20% of which is in the Canadian Arctic (CAFF, 2013). Moreover, Canada is the country with the longest coastline in the world (approximately 16% of the world coastline), the majority of which is located in Arctic waters (Archambault *et al.*, 2010).

In recent years, high-latitude areas have shown a disproportionate increase in temperature, and their coasts are highly susceptible to a combination of climate change impacts in addition to sea-level rise (Larsen *et al.*, 2014). Sea surface temperature in the Arctic is warming at faster rates than other parts of the globe (Doney *et al.*, 2012): seasonal minimal sea ice extent has decreased by 45,000 km^2/year over the past thirty years and the decrease of summer sea ice has been estimated to be reduced 12.4% per decade (Stroeve *et al.*, 2007; Stroeve *et al.*, 2012). There has also been a commensurate reduction in perennial sea ice and subsequent increase in annual forms of sea ice (Barber *et al.*, 2009; Barber *et al.*, 2014). Simulations project future scenarios ranging from mean reductions of 31% of the annually averaged sea ice area in the Arctic by 2100 (Solomon, 2007), to more extreme projections of complete disappearance of summer sea ice by 2037 (Hoegh-Guldberg & Bruno, 2010). With these changes, it is predicted that by mid-century, shipping routes such as the Northwest Passage, which crosses the Canadian Arctic Coasts, will become more viable in the future, linking the Atlantic and Pacific oceans (Smith & Stephenson, 2013).

Given that 90% of global cargo is transported by commercial shipping (Minchin, 2006), this is expected to result in an increase in traffic and changes in the shipping patterns with implications for the ecosystem. Since, to our knowledge, high-latitudes have not yet experienced significant introductions of non-native species (Ruiz & Hewitt, 2009; Ware *et al.*, 2014); only predictions of changes can be done to see how the region can be affected.

Predictions of species with higher probabilities of introduction and survival based on habitat suitability are essential for pro-active management strategies. Ideally, management should include a pre-invasion planning phase, since once an introduced species is established, eradication is difficult and in many cases, impossible (Locke & Hanson, 2009; Floerl, 2014). Predictive information can help managers identify vulnerable habitats and determine where and how to monitor species of concern (Locke & Hanson, 2009; Reiss *et al.*, 2014). Species distribution modelling (SDM) is a powerful tool that can be very effective for predicting habitat suitability for species (Elith & Leathwick, 2009), thus providing important information for management (Peterson, 2003). Although SDM has been applied to marine taxa, these studies are less common than in terrestrial taxa (Robinson *et al.*, 2011).

Given that the majority of introduced marine species are benthic (Streftaris *et al.*, 2005), it is of interest to study these organisms and predict those that could potentially be introduced in the Canadian Arctic. Up to ten AIS have been found in Alaskan waters (Hines *et al.*, 2000a; Ruiz & Hewitt, 2009), and new arrivals and introductions in boreal and high-latitude regions have been described in recent years (Ashton *et al.*, 2008a; Svavarsson & Dungal, 2008; Lambert *et al.*, 2010; Gíslason *et al.*, 2014; Chan *et al.*, 2015). Moreover, new species have been discovered for the first time but whose origin is uncertain (MacDonald *et al.*, 2010; Goldsmit *et al.*, 2014). For the Canadian Arctic, there has only been one potential introduced species due to shipping, the red algae *Dumontia contorta* reported by Mathieson *et al.* (2010), and seven species have been recently identified as cryptogenic (new species that could be either native or non-native) (Goldsmit *et al.*, 2014).

However, this region is undersampled as few systematic surveys have been conducted (Archambault *et al.*, 2010; Piepenburg *et al.*, 2011; CAFF, 2013; Roy *et al.*, 2014).

Projected changes in the Arctic will result in warmer, less saline ocean conditions (Carmack & McLaughlin, 2011), which together with increased shipping activity, are expected to favour the establishment of ship-mediated invasive species. Increasing temperatures are also expected to result in shifts in aquatic communities with southern species expanding their ranges to more northern locations (Beaugrand *et al.*, 2010; Villarino *et al.*, 2015; Wisz *et al.*, 2015). It is within the context of this changing environment that the objective of this study is to predict the habitat suitability of a suite of known AIS connected to Canadian Arctic ports and to assess their likelihoods of survival and establishment under both current conditions and under a future scenario of climate change. SDM provides a good approach to address these questions based on known global environmental ranges of the species.

MATERIALS AND METHODS

Study region and shipping activity

Shipping plays a key role in supporting Arctic communities and the economy by transporting resources via domestic and international shipping pathways. The majority annual number of vessel arrivals in the Canadian Arctic are destined for ports in the Hudson Complex region (Hudson Strait, Hudson Bay, Foxe Basin, James Bay and Ungava Bay) (Chan *et al.*, 2012). Although few ballast water discharges occur in the Canadian Arctic in general, the risk associated with individual discharges of international transoceanic vessels is considered to be high (Casas-Monroy *et al.*, 2014).

Species studied

Potential invaders were classified according to the number of barriers they have to introduction and establishment (e.g., environmental conditions, potential connection through shipping, etc.) and according to documented information in published articles

(Hines *et al.*, 2000b; Ruiz *et al.*, 2006; Molnar *et al.*, 2008; Chan *et al.*, 2012), grey literature and global invasive species lists available on the web: National Exotic Marine and Estuarine Species Information System NEMESIS (www.invasions.si.edu/nemesis/), Invasive Species Compendium (www.cabi.org/isc), the European Network on Invasive Alien Species NOBANIS (www.nobanis.org/) and the Global Invasive Species Database GISD (www.issg.org/database). First, a pre-screening step was done to select species for further research with biological-ecological features that could potentially allow for survival in arctic conditions (known temperature and salinity ranges for the species needed to coincide with environmental conditions on the Arctic). The potential of arriving to the Canadian Arctic via shipping traffic was also considered (potential of being transported through ballast water and/or hull fouling from connected ports). The second step involved ranking these species following Ricciardi and Rasmussen (1998). Using this protocol, the potential invasion success of different aquatic organisms was predicted using documented information on: 1) potential donor regions and dispersal pathways of future invaders, 2) biological criteria of selected potential invaders (e.g., abundant in native range, rapid growth, high reproductive capacity, mechanisms for rapid dispersal, etc.) and 3) invasion history. A subset of eight potential invaders with high relative threat for the Canadian Arctic was identified.

The final species list included: 1) the bay barnacle *Amphibalanus improvisus* (Darwin, 1854), 2) the violet tunicate *Botrylloides violaceus* Oka, 1927, 3) the Japanese skeleton shrimp *Caprella mutica* Schurin, 1935, 4) the green crab *Carcinus maenas* (Linnaeus, 1758), 5) the periwinkle *Littorina littorea* (Linnaeus, 1758), 6) the coffin box bryozoan *Membranipora membranacea* (Linnaeus, 1767), 7) the soft-shell clam *Mya arenaria* Linnaeus, 1758 and 8) the red king crab *Paralithodes camtschaticus* (Tilesius, 1815). These species are known invaders that are present in ports connected to Canadian Arctic ports, either by domestic and/or international shipping (Turcotte & Sainte-Marie, 2009; Jørgensen & Nilssen, 2011; Chan *et al.*, 2012) and could potentially be transported through ballast water or biofouling. Table 4 summarises the characteristics of each species.

Table 4: Characteristics of aquatic invasive species used in the modelling analysis.

Species	Native range	Introduced range	Biology / ecology of the species	Impact	References
Amphibalanus improvisus	Western Atlantic Ocean	Europe, California, Pacific Ocean and Australasia	Filter feeder Euryhaline Grows on hard surfaces Hermaphroditic Planktonic larvae T°: -2 to 35°C Salinity: 2 to 40 PSU Intertidal-Subtidal	Economic loss to installations in power plants Slows down vessel's speed Economic impact in the Baltic Sea	Southward (1957), Carlton (1979), Furman and Yule (1991), Dineen Jr and Hines (1992), Bousfield (1955), Leppäkoski and Olenin (2000), Iwasaki (2006), Carlton *et al.* (2011)
Botrylloides violaceus	Northwest Pacific: Japan, Korea and China	Northeast Pacific, Northwest Atlantic and parts of the Northeast Atlantic	Colonial tunicate Asexual reproduction Lecithotrophic larvae T°: -0.6 to 27.4°C Salinity: 20 to 38 PSU Subtidal	Due to abundance and dominance, it can affect shipping and aquaculture Competes for space and food with native fouling organisms	Van Name (1945), Nishikawa (1991), Epelbaum *et al.* (2009), Zerebecki and Sorte (2011), Simkanin *et al.* (2012)
Caprella mutica	Northwest Pacific	Pacific and Atlantic coasts, North America, Europe and New Zeeland	Tolerant and flexible with habitat and feeding Dense populations Related to artificial structures T°: -2 to 20°C Salinity: 14.6 to 40 PSU Subtidal	Affects aquaculture Competition Limited economic and ecological impact studies	Inglis *et al.* (2006), Ashton *et al.* (2007), Cook *et al.* (2007), Locke *et al.* (2007), Ashton *et al.* (2008b), Turcotte and Sainte-Marie (2009), Boos *et al.* (2011)
Carcinus maenas	Atlantic Europe, western Baltic and west of Africa	From Northwest and west of Atlantic to both coasts on the Pacific	Generalist predator Marine and brackish waters High fecundity T°: 3 to 17°C Salinity: 13 to 54 PSU Intertidal-subtidal	Changes in benthic communities due to predation and competition Can affect fisheries and aquaculture	Broekhuysen (1936), Williams (1984), Lowe *et al.* (2000), Carlton and Cohen (2003), Klassen and Locke (2007)
Littorina littorea	European North Atlantic	Atlantic and Pacific coast of North America	Herbivore Estuarine and brackish Planktonic larvae Can withstand freezing T°: 0 to 28°C Salinity: 10 to 40 PSU Intertidal	Alters intertidal ecosystems through grazing Competition Affects diversity, abundance and distribution of animals and plants	Murphy (1979), Carlton (1992), Chase and Thomas (1995), Reid (1996), Chang *et al.* (2011)
Membranipora membranacea	Europe: from the Barents Sea to the Atlantic coast of Spain	Northwest Atlantic, Southern Hemisphere	Encrusted in seaweed beds Marine habitats Long stage of planktonic larvae T°: -1.8 to 26°C Salinity: 8 to 27 PSU Intertidal-subtidal	Fouling in ships and buoys Economic: cultured kelp beds Competition Change of habitat	Yoshioka (1982), Berman *et al.* (1992), Hayward *et al.* (1998), Schwaninger (1999), Saunders and Metaxas (2007), Saunders and Metaxas (2008), Griffiths *et al.* (2009), Gendron *et al.* (2010)

Species	Native range	Introduced range	Biology / ecology of the species	Impact	References
Mya arenaria	Northwest Atlantic, from Labrador to North Carolina (uncertain limits)	Northeast Atlantic	Burrower Bays and Estuaries Planktonic larvae T°: -2 to 28°C Salinity: 5 to 35 PSU Intertidal – subtidal – deeper waters	Difficult to identify impacts: introduced in Europe for more than 500 years Decrease in biomass of native species High filtration capacity	Morgan *et al.* (1978), Englund and Heino (1994), Obolewski and Piesik (2005), Petersen *et al.* (2008)
Paralithodes camtschaticus	North Pacific, Japanese Ocean and Bering Sea	Barents Sea (intentional introduction)	Generalist predator Planktonic larvae T°: -1.7 to 11°C Salinity: information not available Subtidal – until 300m depth	Predation: can change native biodiversity in species number and biomass	Orlov and Ivanov (1978), Rodin (1989), Pavlova *et al.* (2007), Oug *et al.* (2011)

Environmental data

The environmental variables used were those that are typically the most important limiting factors for benthic aquatic species: temperature and salinity (bottom and sea surface), ice concentration and bathymetry (Table 5). To build, train and validate the model, monthly averaged climatological values were used for a 30-year period time (1981-2010) using global scale environmental data at 1° resolution. Temperature, salinity and bathymetry were obtained from the World Ocean Atlas 2013 (Boyer & Mishonov, 2013). Sea ice cover was obtained from the Sea Ice Index (Fetterer *et al.*, 2002) and from the Met Office Hadley Centre (Rayner *et al.*, 2003).

Table 5: Environmental variables information used in the habitat suitability models.

Variables	Data type	Calculation type	Units	Source
Sea surface temperature/ Bottom temperature	Maximum Minimum Mean	Monthly mean	°C	World Ocean Atlas (Boyer & Mishonov, 2013)
Sea surface salinity/ Bottom salinity	Maximum Minimum Mean	Monthly mean	PSU	World Ocean Atlas (Boyer & Mishonov, 2013)
Sea ice	15% ice coverage 50% ice coverage	Ice concentration	Length (in months) of open water period at a global scale	Sea Ice Index (Fetterer *et al.*, 2002)
Sea ice	50% ice coverage	Ice concentration	Length (in months) of open water period at a global scale	Met Office Hadley Centre (Rayner et al. 2003)
Bathymetry			Meters	World Ocean Atlas (Boyer & Mishonov, 2013)

Distributional data

Global scale occurrence data (native and invaded ranges) were compiled for each species from global databases such as the Global Biodiversity Information Facility GBIF (www.gbif.org), Ocean Biogeographic Information system OBIS (www.iobis.or), invasive species lists with available coordinate location information and specific literature (Appendix IV). Larger sampling sizes result in better models (Guisan *et al.*, 2007a; Guisan *et al.*, 2007b) and efforts should be focused on the improvement of the number and quality of occurrence records (Lobo, 2008; García-Roselló *et al.*, 2015). Hence, we focused our effort on finding the highest number of occurrence records possible for each species. The numbers ranged from 81 occurrence points (*C. mutica*) to 189 (*M. arenaria*) (Appendix IV). Only one presence record was counted per grid (1° resolution) to decrease any probable overprediction (García-Roselló *et al.*, 2015). With this approach a sample unit of size equal to the grain size of the environmental variables is assumed. The ecoregion names used in the text were according to the bioregionalization made by Spalding *et al.* (2007).

Habitat suitability modelling

The relationship between species' records and the environmental characteristics in a specific region can be assessed in SDM in order to estimate the habitat suitability for a given species. MaxEnt 3.3.3k (Phillips *et al.*, 2006) was the model used to predict the species' habitats (http://www.cs.princeton.edu/~schapire/maxent/). MaxEnt is one of the most widely utilized SDM algorithms (Elith *et al.*, 2011). It is a machine learning method based on maximum entropy for modelling species geographic distributions with presence-only data, by relating occurrence data and environmental variables. It has been found to outperform other methods, show a high predictive accuracy and be better able to model range shifts under future climate change scenarios (Elith *et al.*, 2006; Hijmans & Graham, 2006; Pearson *et al.*, 2007).

Correction for spatial bias is highly recommended for predicting future trends in SDM to avoid sampling habitat outside the species' known occurrence and for collection sampling bias (Brown, 2014; Hertzog *et al.*, 2014). Hence, bias files were included during model building using the SDMtoolbox package in ArcGIS (Brown, 2014). Cross-validation was used to evaluate the predictive power of the model: 70% of the occurrence points were chosen randomly and used to train the model, while the other 30% were used to test it. The convergence threshold was set at 0.00001, 500 iterations were made and random seed was used to select training points. The hinge feature was used since it produces complex but smoothed and ecologically meaningful response curves and it improves model performance (Phillips & Dudík, 2008; Merow *et al.*, 2013). Continuous values were transformed into binary values (suitable/not suitable) by applying the maximum training sensitivity plus specificity threshold. This threshold is known to produce the most accurate predictions, especially for presence-only datasets (Jiménez-Valverde & Lobo, 2007; Liu *et al.*, 2013).

We opted to use fewer environmental predictors at a coarser resolution, but of high quality for the region of study (lowest possible grids with extrapolated data for pixels with missing data), rather than increasing the number of variables and the resolution with a corresponding loss of data quality. The model was constructed accordingly with the most important variables for each species (Appendix V). This was evaluated by: 1) the response curves for each variable, indicating which particular environmental conditions within a range were most suitable for each species (unimodal shape corresponded to ecological and biological meaning within the Hutchinson (1957) niche theory framework); 2) a species-specific Jackknife test built with all the variables alone and by excluding each variable sequentially; and 3) a table showing the percentage contribution of each variable. The area under the curve (AUC) was used to evaluate the performance of the model. In presence-only models, the AUC is the probability that the model correctly ranks a random presence site vs. a random site from the study area (Phillips *et al.*, 2009). The model runs were corrected using a mask for maximum depths each species could inhabit according to their ecological requirements (Table 4).

Prior to model fitting, autocorrelation between environmental variables was checked to prevent inclusion of other correlated variables. This was calculated using the

SDMtoolbox (Brown, 2014). Variables with correlation coefficients equal or higher than 0.7 were considered significant (Dormann *et al.*, 2013) and only one of them were included in the same species-specific model construction.

Future projection under climate change scenario

Once the SDM global models were built and validated under present environmental conditions, the projections of habitat suitability were undertaken using future projected environmental layers for the Arctic and North Atlantic. Future environmental variables were the same as the ones used to build the model under current conditions (Table 5), but were based on projected data generated from the validated ocean-sea ice model from the Nucleus for European Modelling of the Ocean NEMO forced with the input from the Model for Interdisciplinary Research on Climate MIROC5 (Madec, 2008; Watanabe *et al.*, 2010). The RCP4.5 emission scenario was chosen, corresponding to an intermediate greenhouse emission (temperature anomaly of 2.4°C by 2100) (Moss *et al.*, 2008). The model has a higher resolution than the one used for building and training the SDMs' (1/4° in general, ~1/8° in Hudson Bay and ~1/18° in the Canadian Archipelago); it begins in 2006 and projects environmental changes in the ocean and sea ice until 2050. Two time series were used: 2006-2015 to represent the present time with the projected model, and 2045-2050 to make the projections into the future.

The resulting future habitat suitability models were compared with the present ones. The latitudinal shift in suitable habitat was spatially analyzed using ArcMap to illustrate the suitable areas i) only in the present, ii) only in the future and iii) in both present and future timeframes. The percentage change in the area of habitat suitability between present and future conditions was calculated.

RESULTS

Habitat suitability in the present

Based on model predictions, all species had suitable habitat in their known ranges, indicating that the accuracy of models was adequate. Suitable habitat for all eight species was also predicted in other locations where the species are not known to currently occur, indicating that existing environmental conditions are suitable for those species elsewhere (Figure 12). Regions of the Canadian Arctic were shown to be already suitable under current conditions for *Littorina littorea*, *Mya arenaria* and *Paralithodes camtschaticus* (Figure 12).

Latitudinal shift

Based on estimated potential latitudinal changes in habitat suitability with future climate warming, all species were predicted to have increased suitable habitat towards the Canadian Arctic (Figure 13). Even though all species showed a poleward/sub-poleward shift, there were species-specific differences in the magnitude and regions of distributional shifts. For example, for *L. littorea*, *M. arenaria* and *P. camtschaticus*, shifts in suitable habitats were mostly in regions that were already suitable under present environmental conditions. In contrast, all the remaining species showed new suitable regions only in the future together with some extended regions of suitable habitat where they are already present. One of the most noteworthy new suitable regions under future environmental conditions was the Hudson Complex.

All species showed gains in habitat suitability in the future with the exception of *P. camtschaticus*. The percentage gain in area of suitable habitat between the present and future models was highest for *M. membranacea* and *M. arenaria* (+28.9% and +23.4% respectively), and the lowest was for P. *camtschaticus* (-0.1%), showing a small loss in its habitat percentage shift (Figure 13).

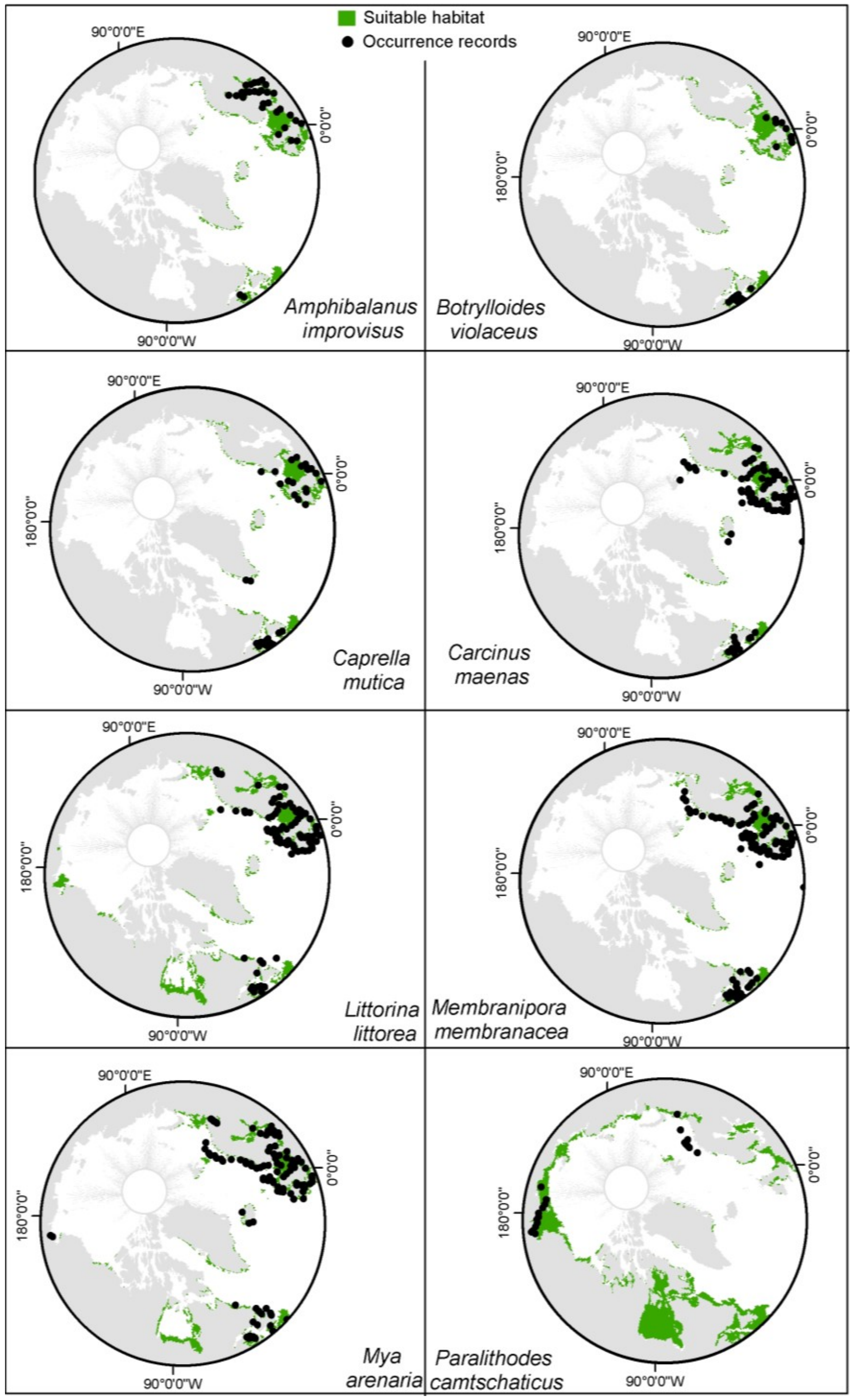


Figure 12: Habitat suitability for the present projected into the Arctic and North Atlantic Oceans only. Habitat suitability is shown in binary values (suitable/not suitable) in green and occurrence records are shown as black dots.

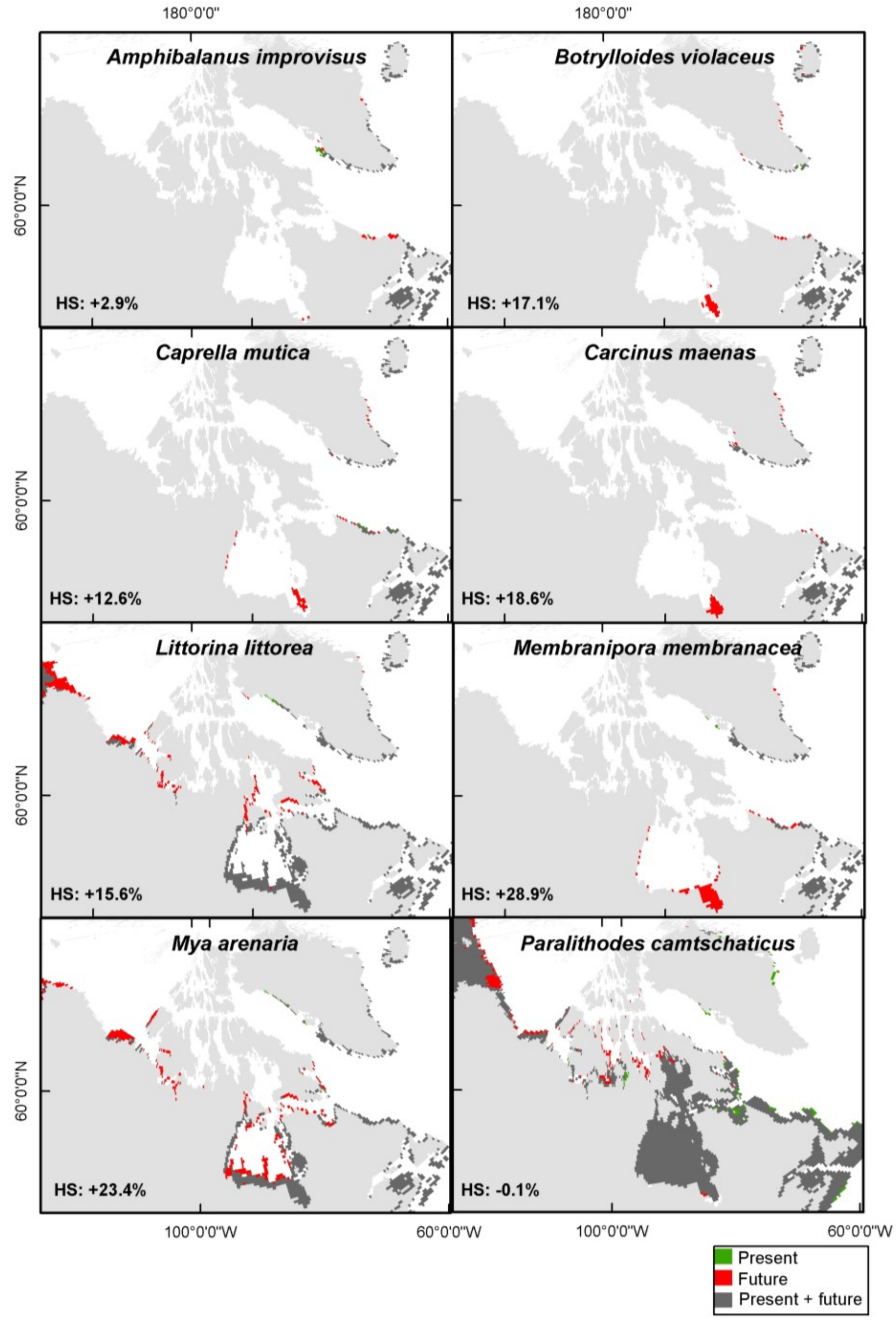


Figure 13: Habitat suitability for the present and the future projected into the Canadian Arctic. Percentage of gain (+) or loss (-) in habitat suitability (HS) is shown for each species. Shaded green area is the habitat suitability only in the present, red corresponds to habitat suitability only in the future and shaded dark grey to the area suitable both in the present and in the future.

Model evaluation

All models had high values of AUC (>0.9) and low values of error rates (Table 6) providing a high confidence in predicting power. The maximum training sensitivity plus specificity thresholds used were also low for all species (P-values < 0.0001). The analysis of unimodal shape environmental response curves indicated that environmental conditions were within suitable ranges for each of the species modelled.

Most of the environmental variables were found to be inside their training range, with the exception of two regions: the Baltic Sea and the high Arctic Circle. This means that these last areas have one or more environmental variables outside the range present in the training data. These environmental variables were sea surface temperature and sea surface salinity; therefore, predictions in those areas should be treated with caution. All models were built taking into consideration the high correlation between ice concentration and maximum sea surface temperature (R>0.7), and only the one that was playing a major role in the distribution of the species was considered (Appendix V).

Table 6: Model parameters and evaluation indicators: Area under the curve (AUC) and threshold values obtained for each species.

Species	**AUC**	**SD**	**Threshold**
Amphibalanus improvisus	0.958	0.023	0.1641
Botrylloides violaceus	0.975	0.017	0.0802
Caprella mutica	0.985	0.014	0.1986
Carcinus maenas	0.935	0.024	0.1694
Littorina littorea	0.978	0.008	0.039
Membranacea membranipora	0.975	0.006	0.1505
Mya arenaria	0.968	0.018	0.0591
Paralithodes camtschaticus	0.984	0.005	0.0364

DISCUSSION

Regional and species-specific models can aid in the identification of high threat areas/species to allow for more focused AIS monitoring and research efforts. The habitat suitability modelling performed in this study with a suite of potential ship-mediated aquatic invasive species identified habitat suitability in areas where these species are not currently known to occur. For three of the eight species modelled there were suitable regions for establishment in the Canadian Arctic, indicating that this region is currently under threat of introduction, especially in the Hudson Complex. Under the climate scenario projection by 2050, all eight species were projected to have suitable habitat in at least some regions of the Canadian Arctic. Although the complete suite of species used in this study showed a poleward/sub-poleward latitudinal shift in suitable habitat by mid-century, its extent varied among species. These results, based solely on environmental factors affecting habitat suitability, indicate that the Arctic regions and the Canadian Arctic in particular, have a high threat of introduction that will increase with time. This risk will be further accentuated if we consider the fact that future shipping is predicted to be much higher in this region, increasing the probability for transport of new species into the area (Smith & Stephenson, 2013; Miller & Ruiz, 2014).

All modelled species revealed suitable habitats in places outside their actual range. This is consistent with the knowledge that invasive populations frequently occupy new environments relative to their native ranges (Compton *et al.*, 2010). The prediction that all species currently have suitable habitats in places outside their actual observed ranges suggests that habitat conditions are suitable not only where the species occur, but also beyond it. This may be partly explained by dispersal limitation of the species and niche size (Pulliam, 2000). In the present study, the periwinkle *Littorina littorea*, the soft shell clam *Mya arenaria* and the red king crab *Paralithodes camtschaticus* were predicted to have suitable habitats in the Canadian Arctic under current environmental conditions. These results are not surprising in the case of *L. littorea* and *M. arenaria*. The former is well established in the Gulf of St-Lawrence as well as in cooler waters along Newfoundland's coast, and there are records of the species along the Northeastern coast of North America since the 1800's (Chapman *et al.*, 2007). The most supported hypotheses of introduction of the periwinkle in North America are the transport by rock ballast and intentional transportation as a food resource (Brawley *et al.*, 2009). In the case of *M. arenaria*, there are records along cold water regions such as Labrador, Iceland and Alaska (Morgan *et al.*, 1978). The soft-shell clam has become a successful invader by natural migration, through aquaculture and transportation by ballast water (Strasser, 1998). These two species have long larval periods in their life cycles and are currently present in ports that are connected to Canadian Arctic ports via vessels that may transport organisms through hull fouling and/or ballast water (Chan *et al.*, 2012), presenting a current risk of introduction to the region. The case of *P. camtschaticus* is different due to its history of invasion. It has been intentionally released in areas where it is currently established to create an economic resource and there have been no records of ballast water transport in the region (Orlov & Ivanov, 1978). Nevertheless, there is the possibility that the larvae can be transported in ballast water, and considering that there is shipping activity due to oil and gas reserves around the Barents Sea and Norway, there is the potential for port connections and introductions to the Canadian Arctic (Jørgensen & Nilssen, 2011). Also of concern is that its predicted habitat suitability encompasses a vast portion of the study area.

Arctic regions have not been widely addressed concerning threat of specific AIS making our projected habitat suitability study difficult to compare with others. For most of the AIS considered in this study, this is the first time that SDM has been done for this region. However, the green crab *Carcinus maenas* and the bay barnacle *Amphibalanus improvisus* have been more extensively studied and can be considered here for discussion. The bay barnacle has shown a large amount of suitable habitat north of its current range when modelled in Alaskan coasts under global warming conditions (de Rivera *et al.*, 2011). On the other hand, the green crab has a very wide projected suitability in high latitudes, but at a global scale, the introduction likelihood is very low (de Rivera *et al.*, 2011; Crafton, 2014). Commercial shipping is considered the most likely vector for introduction, however given that major ports at a global scale are at a considerable distance from high-latitude ports, this makes the likelihood of arrival low for these regions given that it is more likely that organisms can die in transit (Crafton, 2014). Although at a global scale Canadian Arctic ports are considered to have relatively low annual likelihood of introduction through ballast water, this risk is expected to increase due to the longer open-water period, global warming and increase in resource exploitation (Smith & Stephenson, 2013; Gavrilchuk & Lesage, 2014; Pizzolato *et al.*, 2014; Ware *et al.*, 2014; Casas-Monroy *et al.*, 2015). A clear example of this situation is the number of shipping transits in the Canadian Arctic that has already increased substantially in the last few years (Ruffilli, 2011).

Future northward shifts are also supported by other studies considering climate change and species distribution predictions on other marine groups such as fish, invertebrates, zooplankton and seagrass (Cheung *et al.*, 2009; Beaugrand *et al.*, 2010; Chust *et al.*, 2013; Valle *et al.*, 2014; Villarino *et al.*, 2015; Wisz *et al.*, 2015). Our results showed that all species were predicted to shift their habitat suitability poleward/sub-poleward by mid-century. This agrees with the results from Cheung *et al.* (2009), who also predicted a high intensity of invasions by fish and marine invertebrates in high latitude regions by mid-century. Crustaceans, ascidians and gastropods have also been predicted to have future northward shifts in other high-latitude parts of the world (de Rivera *et al.*, 2011). New regions will be suitable in the future for most of the species modelled in our study, especially in the Hudson Complex in the Canadian Arctic. Global warming could provide new opportunities for species introductions to areas where they are not able to survive currently (Walther *et al.*, 2009). This increases the likelihood of future introductions in the region, given that most of the species modelled in this study are present or established in ports that are connected to the main Canadian Arctic ports (Chan *et al.*, 2012).

All species presented a positive increase in total areal extent of future suitable habitat, with the exception of *P. camtschaticus*. The latter resulted in a negative percentage in habitat suitability extension in the future, losing 0.1%. This can be interpreted as nearly no net difference between the predicted habitat suitability in the present compared to the future. For the other species, the finding is consistent with the shifts estimated for other marine organisms under climate change scenarios (Cheung *et al.*, 2009; Valle *et al.*, 2014). The predicted shifts in the current modelling study are supported by experimental evidence based on thermo-tolerance of invasive species such as *C. maenas*, which have been shown to tolerate thermal conditions year round beyond what their current range limits would suggest (Kelley *et al.*, 2013). Similar testing and modelling in other invasive species has shown that temperature is the most influential factor for habitat suitability (Capinha & Anastácio, 2011). It has further been shown that in addition to environmental variables, phenotypic plasticity of some invasive species has rendered previously unsuitable environments increasingly vulnerable (Kelley *et al.*, 2013).

The use of SDM is fundamental to evaluating how climate change can affect future introduced species, biodiversity and the associated ecosystems. These models should be viewed as a first approximation of the potential impact of climate-induced landscape change on biodiversity (Pearson & Dawson, 2003). Understanding the restrictions of the model can lead us to see the usefulness of the results and the applicability while being aware of limitations. Given that the predictions in our study were in a different region from the species source area and that the results were projected into the future, there were several considerations in the interpretation of the model results: 1) the use of abiotic factors only, 2) the selection of environmental variables used, 3) the choice of the model used for the SDM analysis and 4) the climate change projection models used to predict future environmental conditions.

Biotic interactions were not addressed in our SDM since it relates species occurrence to spatially abiotic factors (Guisan & Zimmermann, 2000). Even though the importance of the biotic interactions in shaping the spatial distributions of a species is recognized (Wisz *et al.*, 2013), in our case it was not possible to include this variable due to lack of information. Much more research effort on basic ecology is required to cover the inclusion of biological factors (Reiss *et al.*, 2014). Since our objective was to project species distributions into a new environment as well as into the future, it was difficult to predict what the possible future interactions might be. Furthermore, there are studies indicating that at a wider scale, species distributions are dominated and influenced by mainly abiotic factors (Pearson & Dawson, 2003).

The selection of environmental variables used for each species is an important step in model building. Including all available variables can result in a lower predictive power due to collinearity and model overparameterization (Tyberghein *et al.*, 2012). In this study, correlation between variables was calculated and accounted for in the analysis. For example, *C. maenas* was only modelled with a few variables given that its response curves and the variables that contributed to explaining known distribution patterns were minimal. This is supported by experimental and modelling studies showing that temperature is the most important variable in predicting the locations where invasive species, such as the green crab, may establish (Compton *et al.*, 2010; Kelley *et al.*, 2013). On the other hand, salinity can sometimes play only a minor role (Compton *et al.*, 2010), and thus was not always included in predicting invasive ranges.

MaxEnt is one of the best models for projecting species range shifts under future climate change (Hijmans & Graham, 2006). However, this kind of procedure should be treated with caution since it involves extrapolating models to novel combinations of environmental variables (Merow *et al.*, 2013). Predicting future changes inevitably comes with a degree of uncertainty (Wenger *et al.*, 2013). Clearly, if the emission scenario or the prediction of the year would be different in the modelling, the results would likely be different as well. The NEMO model has also limitations, including those associated with model horizontal spatial resolution. Both the coupled ocean-sea ice and the atmospheric forcing model are expected to have limitations in future projections particularly in the areas of hydrological forcing of the system and the response of sea ice type and concentration. For the version used in this study, NEMO is considered appropriate for processes with horizontal spatial scales exceeding 10 km. However, the low spatial resolution of the atmospheric variables used to force NEMO may introduce bias in high-resolution ice-ocean simulations (Hu & Myers, 2014).

Studies in prediction of invasive species in the Arctic are rare, making the present work a valuable contribution to the prediction and understanding of the future changes in this region. Predictive studies like this one can provide information for early warning systems and help focus monitoring efforts on vulnerable habitats in marine environments associated with shipping activity (Reiss *et al.*, 2014). This study reveals that the Canadian Arctic and northern high-latitudes in general are already suitable for many non-indigenous species and that this suitability will continue to increase. Future studies need to be done to complete the findings on the present study together with the estimation of likelihood of arrival and combining it with the potential impact that the species may have in the region. Changing environmental conditions together with increasing shipping activity, will favour the establishment of high threat ship-mediated invasive species. This valuable information can help managers to know where and how to monitor species of concern and vulnerable habitats.

ACKNOWLEDGEMENTS

Special thanks to K. Adair, J. Higdon and N. Casajus for help in collating/preparing data, and to C. McKindsey and T. Therriault for valuable comments and suggestions for improving the work. We are grateful for funding from the Natural Sciences and Engineering Research Council's (NSERC) Canadian Aquatic Invasive Species Network (CAISN), the Fisheries and Oceans Canada Aquatic Climate Change Adaptation Service Program (ACCASP), the Nunavut Wildlife Management Board (NWMB) and Quebec-Ocean. We also acknowledge the contributions of Dr. Youyu Lu, as well as the Canada Excellence Research Chair (CERC) and Canada Research Chair (CRC) programs. This work is a contribution to the ArcticNet Networks of Centers of Excellence and the Arctic Science Partnership (ASP) asp-net.org.

APPENDIX IV: OCCURRENCE RECORDS OF SPECIES MODELLED

Occurrence points and sources used for each species modelled.

Species	Occurrence points	Sources
Amphibalanus improvisus	139	GBIF, OBIS, NEMESIS
Botrylloides violaceus	83	GBIF, OBIS, NEMESIS
Caprella mutica	81	GBIF, OBIS, NEMESIS, Buschbaum and Gutow (2005), Frey *et al.* (2009), Willis *et al.* (2004)
Carcinus maenas	173	GBIF, OBIS, NEMESIS
Littorina littorea	118	GBIF, OBIS
Mya arenaria	189	GBIF, OBIS
Membranipora membranacea	145	GBIF, OBIS
Paralithodes camtschaticus	116	GBIF, Jørgensen and Nilssen (2011), Oug *et al.* (2011)

APPENDIX V: ENVIRONMENTAL VARIABLES USED IN THE MODELS

Variables used to build the habitat suitability model for each species.

	SST			SSS			BT			BS			Sea ice			Bathym.
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	15a	50a	15b	
Amphibalanus improvisus		X		X										X		X
Botrylloides violaceus			X											X		X
Caprella mutica		X		X							X			X		X
Carcinus maenas		X												X		X
Littorina littorea		X											X			X
Membranacea membranipora		X		X										X		X
Mya arenaria		X				X									X	X
Paralithodes camtschaticus				X			X				X			X		X

SST: Sea Surface Temperature, SSS: Sea Surface Salinity, BT: Bottom Temperature, BS: Bottom Salinity, Sea ice 15a and 50a: 15 and 50% ice coverage from the Met Office Hadley Centre database (Rayner *et al.*, 2003), Sea ice 15b: 15% ice coverage from the Sea Ice Index database (Fetterer *et al.*, 2002).

CHAPITRE 3
ÉVALUATION DES RISQUES ÉCOLOGIQUES DES INVASIONS MARINES PRÉDITES DANS L'ARCTIQUE CANADIEN

RÉSUMÉ

Le changement climatique global conduit à des variations des conditions environnementales, notamment sur le plan de la température et de la couverture de glace dans les régions de hautes latitudes. Les modèles prédictifs et l'évaluation des risques sont des outils clés pour comprendre les changements potentiels associés aux effets sur les régions côtières. La présente étude est une évaluation des risques écologiques quant aux futures incursions d'espèces envahissantes dans l'Arctique canadien. Les espèces évaluées sont le bigorneau *Littorina littorea*, la mye commune *Mya arenaria* et le crabe royal rouge *Paralithodes camtschaticus*. Ces espèces, connexes aux ports de l'Arctique canadien, ont le potentiel d'être introduites par les activités de navigation lors de la décharge des eaux de ballast. La région a été exposée à un risque différent selon le port et l'année et montre des différences temporelles et spatiales. En général, le déballastage des bateaux domestiques pose un risque plus élevé que le déballastage des navires internationaux. Les principaux ports de Baie Déception et Churchill étaient ceux avec un risque relatif modéré à élevé pour *L. littorea* et *M. arenaria*, surtout depuis les navires domestiques. Dans le cas de *P. camtschaticus*, le risque relatif était faible pour les navires internationaux et nul pour les navires domestiques. Ce travail peut être considéré comme le point de départ pour commencer à établir une liste des espèces à risque potentielles, une liste de surveillance «grise», pour l'Arctique canadien et pour fournir des informations utiles à la prise de décisions futures.

ECOLOGICAL RISK ASSESSMENT OF PREDICTED MARINE INVASIONS IN THE CANADIAN ARCTIC

ABSTRACT

Climate change is impacting environmental conditions, especially with respect to temperature and ice cover in high latitude regions. Predictive models and risk assessment are key tools for understanding potential changes associated with such impacts on coastal regions. The present study is a relative ecological risk assessment for future invasive species incursions in the Canadian Arctic. The species assessed were the periwinkle *Littorina littorea*, the soft shell clam *Mya arenaria* and the red king crab *Paralithodes camtschaticus*. These species are connected to Canadian Arctic ports and have the potential to be introduced by shipping through ballast water discharge. This region has been exposed to different levels of relative overall risk that vary by port and from year to year, highlighting temporal and spatial patterns. In general, domestic discharge events posed a higher relative overall risk on a vessel-specific basis than did international discharges. The main ports of Deception Bay and Churchill were classified as being at moderate to high relative risk for *L. littorea* and *M. arenaria*, especially from domestic vessels. The relative overall risk for *P. camtschaticus* was low for international vessels and null for domestic vessels. This work can serve as a starting point for building a list of potential high risk species – a "grey" watch list – for the Canadian Arctic, and provides useful information for consideration in future decision making actions.

Key words: Ecological risk assessment, ballast water, risk, likelihood of introduction, consequence of occurrence, impact.

The third chapter was co-authored by me, Dr. Kimberly Howland, Dr. Chris Mckindsey and Dr. Philippe Archambault. It will be submitted in the winter session 2016 to the journal *Biological Invasions*. As first author, I conceived the research question and project, together with valuable input of the co-authors. I performed the risk assessment analysis and wrote the manuscript, with the insightful participation of Dr. Howland, Dr. Mckindsey and Dr. Archambault.

An outline of the ideas for this chapter was presented as oral and poster presentations on the 48th Canadian Meteorological and Oceanographic Society (CMOS) in Rimouski (Canada) in June 2014 and in the International Conference on Marine Bioinvasions in Sydney (Australia) in January 2016.

INTRODUCTION

Invasive species and global warming are among the most serious drivers of global environmental change and threaten marine biodiversity (Stachowicz *et al.*, 2002a; Occhipinti-Ambrogi, 2007; Molnar *et al.*, 2008). Successful establishment of an invasive species depends upon its successful completion of a series of transitions, each with independent probabilities of failure (Carlton, 1985; Kolar & Lodge, 2002). Vectors must uptake, transport, and deliver a sufficient number of viable propagules to an area outside of the species' historic range. These individuals must be capable of surviving and reproducing under ambient physico-chemical and biological-ecological conditions (Herborg *et al.*, 2007).

The principal global vector for unintentional introduction of aquatic invasive species is shipping (Carlton, 1985; Ruiz *et al.*, 2000; Molnar *et al.*, 2008). Species may be transported unintentionally during ballast water uptake/discharge and through the accumulation and transport of organisms on vessel surfaces (biofouling) or in protected areas, such as sea chests (Coutts & Dodgshun, 2007; Minchin *et al.*, 2009). The global shipping network is responsible for approximately 90% of global trade (Kaluza *et al.*, 2010; Xu *et al.*, 2014), posing a substantial concern as it is the dominant vector of introduction. The "path length" between any two ports is the minimum number of connections or steps required to travel between them (based on recorded voyages in a given year) (Kaluza *et al.*, 2010). In 2007, the average path length between ports was 2.5 and the maximum was only 8; most source-arrival destination pairs are connected by 2 or less steps (Kaluza *et al.*, 2010). Given that the shipping network is so well connected and important at a global scale, it is important to consider the potential for transport of aquatic invasive species since, once species become established in marine habitats, it is rarely possible to eliminate them (Thresher & Kuris, 2004).

Commercial shipping has contributed between 44 to 78% of the initial invasions of all non-indigenous species to North America (Ruiz *et al.*, 2015). Mid-ocean ballast water exchange (BWE) has been the primary means of reducing the risks of introducing non-indigenous species by transoceanic vessels. The water contained in ballast tanks from coastal ports can be effectively replaced with oceanic water through BWE (e.g., 97-99% efficiency for bulk carriers and tankers). This helps reduce invasion risk by various organisms due to the salinity shock encountered by individuals remaining in tanks following BWE. Although this method has been shown to be very effective for freshwater species (Bailey *et al.*, 2011), its efficacy for coastal marine species is variable (Simard *et al.*, 2011) and may even increase invasion risk if novel (to receiving ports) oceanic species are added during BWE (Cordell *et al.*, 2009).

Sea surface temperature in the Arctic is warming at faster rates than other parts of the globe (Doney *et al.*, 2012); seasonal minimal sea ice extent has decreased by 45,000 km^2/year over the past thirty years and is estimated to be declining at a rate of -13.4% per decade (Stroeve *et al.*, 2007; Meier and Stroeve, 2015). The Arctic is at risk of introductions due to global warming, resource exploitation and increases in project developments, and the associated increase in shipping activity (Smith & Stephenson, 2013; Gavrilchuk & Lesage, 2014; Miller & Ruiz, 2014). Most introductions have occurred in warmer, temperate regions, where there is greater shipping activity, but the rise in shipping activity in the Arctic is expected to increase the risk of exotic species introductions to Arctic waters in the near future (Niimi, 2004; Ware *et al.*, 2014). It is predicted that, by mid-century, new shipping routes will open across the Arctic (e.g., the Northwest Passage that crosses the Canadian Arctic, linking the Atlantic and Pacific oceans) (Smith & Stephenson, 2013). Canada possesses approximately 16% of the world's coastline, making it the country with the longest coastline in the world (Archambault *et al.*, 2010). Most of this coastline is located in Arctic waters, covering almost 20% of the 10 million km^2 of the Arctic Ocean (CAFF, 2013).

Since the majority of introduced marine species are benthic (Streftaris *et al.*, 2005), it is of particular interest to evaluate the potential for these organisms to be introduced in the Canadian Arctic. To date, there have not been any known ship-mediated introductions of benthic invertebrates in the Canadian Arctic (Goldsmit *et al.*, 2014). Nevertheless, recent studies have demonstrated that potential benthic invasive species are already arriving in the region (Chan *et al.*, 2015). There has only been one potential shipping-mediated introduced species reported to date, the red alga *Dumontia contorta,* which was found by Mathieson *et al.* (2010), and seven species have recently been identified as cryptogenic (new species that could be either native or non-native) (Goldsmit *et al.*, 2014). However, more numerous introductions and novel species in other high-latitude areas have been recently reported (Hines *et al.*, 2000a; Ashton *et al.*, 2008a; Svavarsson & Dungal, 2008; Alvsvåg *et al.*, 2009; Ruiz & Hewitt, 2009; Lambert *et al.*, 2010; MacDonald *et al.*, 2010; Gíslason *et al.*, 2014),. Yet, the Canadian Arctic is under sampled with few systematic surveys having been conducted, making the detection of new introductions more difficult (Archambault *et al.*, 2010; Piepenburg *et al.*, 2011; CAFF, 2013; Roy *et al.*, 2014). Given that high-latitudes have yet to experience a significant number of introductions of non-native species (Ruiz & Hewitt, 2009; Ware *et al.*, 2014), we can only predict how these changes could affect the region.

One way of assessing the risk of introduction of new species is to perform risk assessment, which is an effective tool for estimating risk potential in a systematic way (Force, 1996). It is the process by which undesired events (e.g., invasive species introduction) are identified and their consequences parameterized, including uncertainties related to the assessment process (Hewitt & Hayes, 2002). These types of studies can be used to evaluate the invasion potential associated with different shipping pathways and management strategies (Ricciardi & Rasmussen, 1998). Species level risk assessments provide information about the particular risk of a given species and risk is calculated with direct consideration of the characteristics of the organism (Barry *et al.*, 2008). Pre-invasion assessments, which aim to predict the risk of invasion and impact in regions where the species have not yet arrived and/or established, can be useful in trying to prevent undesirable future impacts (Kumschick & Richardson, 2013; Kumschick *et al.*, 2015). The use of watch lists combined with monitoring efforts in regions where the pre-invasion assessment took place can lead to the discovery of the introduced species before they negatively impact the ecosystem (Locke, 2009; Moore *et al.*, 2014).

The aim of the present study is to characterize the relative ecological risk of future invasive species incursions in Canadian Arctic ports, with special emphasis on the development of a species-specific assessment protocol. The proposed methodology is a unique combination of risk components that can enable a comparative analysis between species being assessed and ports that have the potential to receive their propagules through ballast water discharge. This risk assessment framework will provide information that can be used in future management decisions regarding the development of preventive actions to limit new introductions, and act as a starting point to build a list of species with potential risk for the Canadian Arctic.

MATERIALS AND METHODS

Study area

Eight ecoregions of the Canadian Arctic, as delineated by Spalding *et al.* (2007), were considered in this study (Figure 14). Shipping plays a key role in supporting Arctic communities, for the economy and for transporting resources by domestic and international shipping. Three Canadian Arctic ports receive considerably more traffic than do the others: Churchill, Deception Bay and Iqaluit (Figure 14).

Churchill is located on the south western shores of Hudson Bay and is the major seaport in the region; its main activity is the export of grain by international traffic. Churchill receives the highest number of vessels and volume of ballast discharge, and is environmentally similar to a large number of connected source ports with established high risk non-indigenous species (relative to other ports in the Canadian Arctic) (Chan *et al.*, 2012). Shipping activity for the port of Deception Bay is related to two nickel mining sites, one of them exporting concentrate to Quebec, and the other to Europe (Arctic-Council, 2009; Gavrilchuk & Lesage, 2014).

Deception Bay is among the top 3 ports in the Canadian Arctic with respect to number of arrivals and volume of untreated ballast water released for international and coastal domestic merchant vessels. This port was also found to have high environmental similarity with a large number of its source ports, thus increasing the probability of survival of species introduced from linked ports (Chan *et al.*, 2012).

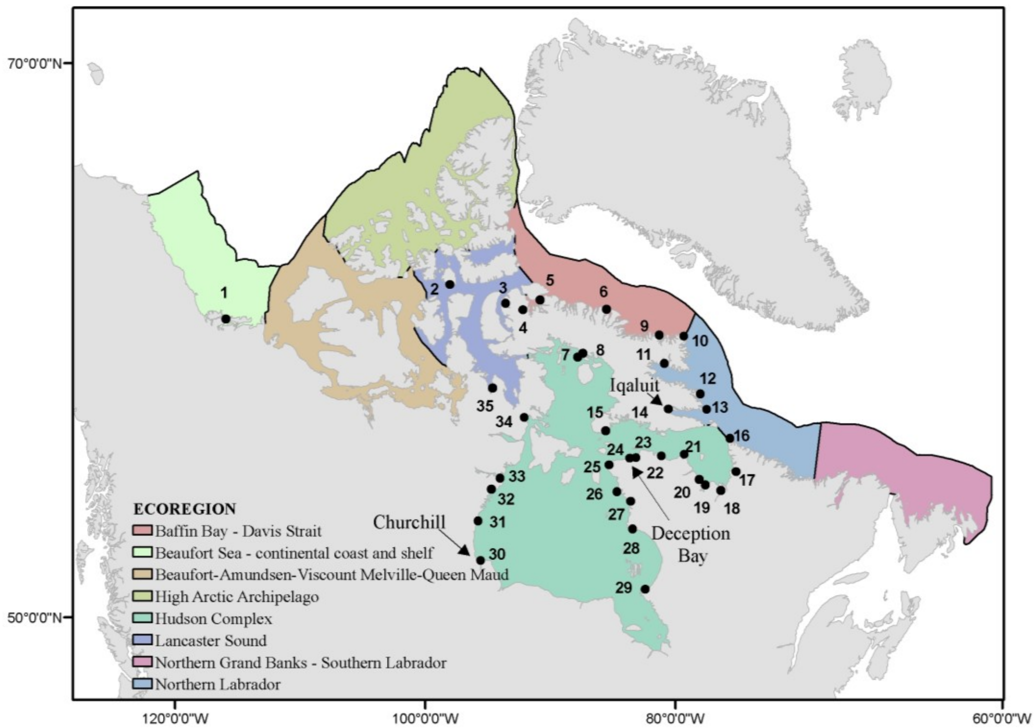


Figure 14: Main arrival ports in the Canadian Arctic and ecoregions. Numbers on the map correspond to port names: Tuktoyaktuk (1), Resolute Bay (2), Nanisivik (3), Milne Inlet (4), Pond Inlet (5), Clyde River (6), Hall Beach (7), Longstaff Bluff (8), Broughton Island (9), Cape Dyer (10) Pangnirtung (11), Breevoort (12), Loks Land (13), Iqaluit (14), Cape Dorset (15), Killinek (16), Kangiqsualujjuaq (17), Kujjuaq (18), Tasiujaq (19), Aupaluk (20), Quaqtaq (21), Wakeham Bay (22), Deception Bay (23), Salluit (24), Ivujivik (25), Akulivik (26), Puvirnituq (27), Inukjuak (28), Kuujjuaraapik (29), Churchill (30), Arviat (31), Rankin Inlet (32), Chesterfield (33), Repulse Bay (34), and Pelly Bay (35).

Iqaluit’s port is used for different activities: dry cargo handling (government, commercial and private use), petroleum, fisheries, tourist cruise ships, military and research vessels, Canadian Coast Guard, and small craft operators including hunters and fishers

(Aarluk-Consulting *et al.*, 2005). The annual volumes of dry goods and petroleum products shipped to Iqaluit have been increasing dramatically, and tourism and other marine activities have also increased markedly since 1980 (Aarluk-Consulting *et al.*, 2005). Iqaluit is characterized by having a high level of international and coastal domestic merchant vessels and international non-merchant arrivals, and it is among the top ports in the Canadian Arctic for invasion risk via hull fouling (Chan *et al.*, 2012). The other ports in the Canadian Arctic (Figure 14) are less active, receiving mostly domestic vessels and a few international vessels with very few ballast discharge events (Chan *et al.*, 2012). Exceptions are ports opening with new developments which are expected to have rapid increases in shipping over coming years (Gavrilchuk & Lesage, 2014). Although some of these (e.g., Milne Inlet, Nunavut, Baffinland Inc.) are expected to exceed the top ports in the Canadian Arctic with respect to future arrivals and discharge, they are not considered within the scope of this assessment which relies on shipping data from the recent past.

Invasive species characterization

To identify potentially invasive species for use as case studies to evaluate the developed risk assessment protocol, factors including the capability of being introduced outside of a species' native range, potential impacts, strength and type of ecological interactions, current distribution and relationship with vectors (e.g., ballast water), need to be identified (David *et al.*, 2015). The species selected for this ecological risk assessment are among those that are invasive elsewhere, not present in the Canadian Arctic but present in ports that are connected to Canadian Arctic ports, and that have predicted habitat suitability in present environmental conditions according to Goldsmit *et al*. (Chapter N°2). These included: 1) the common periwinkle *Littorina littorea*, 2) the soft-shell clam *Mya arenaria* and 3) the red king crab *Paralithodes camtschaticus.* In addition to certain regions of the Canadian Arctic already being suitable for these three species, the predicted extent of suitable habitat will increase under climate change scenarios by mid-century (Goldsmit *et al*., Chapter N°2). The three case species are benthic invertebrates with different invasion histories and different survival strategies, but have the shared characteristic of a larval phase that is long enough to be transported by ballast water (Table 7). Another common characteristic of these species is that all are ecosystem engineers and are thus regarded as high impact/risk species that can influence ecosystem properties and biodiversity (Bouma *et al.*, 2009).

Table 7: Characteristics of aquatic invasive species used in the ecological risk assessment.

Species	Native range	Introduced range	Modes of introduction	Biology / ecology	References
Littorina littorea	European North Atlantic	Atlantic and Pacific coast of North America	Rock-ballasted ships from Great Britain/Ireland in the earlies 1800s	Herbivore Estuarine and brackish 4 to 7 weeks of planktonic larvae Can withstand freezing T°: 0 to 28°C Salinity: 10 to 40 PSU Intertidal	Murphy (1979), Carlton (1992), Chase and Thomas (1995), Reid (1996), Chang *et al.* (2011), Brawley *et al.* (2009), Fretter and Graham (1985), Thorson and Jørgensen (1946)
Mya arenaria	Northwest Atlantic, from Labrador to North Carolina (uncertain limits)	Northeast Atlantic Pacific northeast and northwest coasts	First species known to have been introduced to European waters. Introduced accidentally with imported seed oysters in the late 1800s to the Pacific Coast of North America	Burrower Bays and Estuaries 2-3 weeks of planktonic larvae T°: -2 to 28°C Salinity: 5 to 35 PSU Intertidal – subtidal – deeper waters	Morgan *et al.* (1978), (Goshima, 1982), Englund and Heino (1994), Strasser (1998), Obolewski and Piesik (2005), Byers (2005), Petersen *et al.* (2008), (Carlton, 2011)
Paralithodes camtschaticus	North Pacific, Japanese Sea and Bering Sea	Barents Sea	Intentional introduction in the Barents Sea to create a fishery in 1960	Generalist predator Planktonic larvae (2-3 months) T°: -1.7 to 11°C Salinity: information not available Subtidal – to 300m depth	Orlov and Ivanov (1978), Rodin (1989), Pavlova *et al.* (2007), Oug *et al.* (2011)

Risk characterization

Risk is defined as the combination of the likelihood of an event occurring, and the consequences of the event if it were to occur (Gibbs & Browman, 2015). In this study, "likelihood of an event" is defined as the likelihood of introduction of non-indigenous species (a combination of arrival, survival, and establishment), and "consequence" is defined as the consequence of occurrence that a species could have if it arrives and establishes in a specific location. Overall risk is calculated as the product of likelihood of introduction and consequence of occurrence per port, year and species associated with individual vessel discharges (Figure 15). This is a relative risk assessment since the risk values are compared between ports and species assessed. Methods were adapted and modified from Hewitt *et al.* (2006), Therriault *et al.* (2008) and Mandrak *et al.* (2012). The assessment was done at an ecological level; no economic or social impacts were considered.

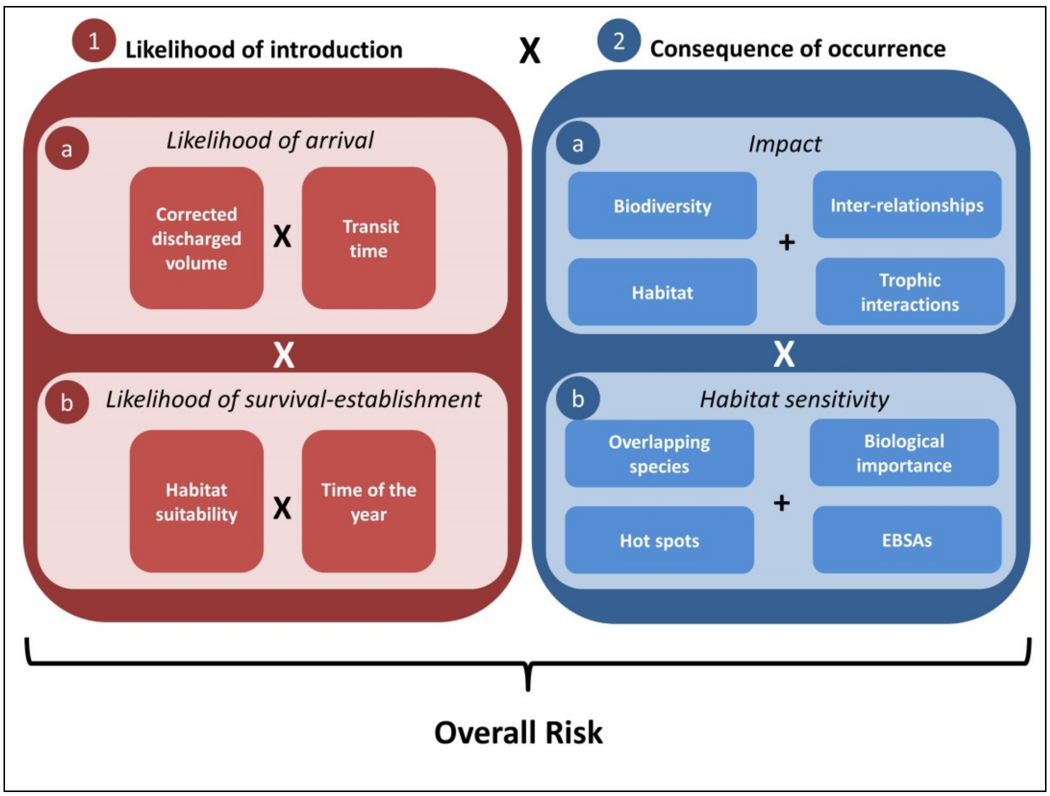


Figure 15: Relative risk assessment diagram showing how the overall risk was calculated: likelihood of introduction (arrival x survival/establishment) combined with the consequence of occurrence (impact x habitat sensitivity).

Likelihood of introduction

The potential for successful species introduction was calculated as the product of: a) likelihood of arrival (ballast water from shipping as the sole vector considered); and b) likelihood of survival-establishment (probability of suitable conditions and habitat available for a given species released in the receiving environment); modified from Mandrak *et al.* (2012) (Section *1* in Figure 15).

The likelihood of arrival was based on shipping information from several databases for vessels that arrived at Canadian Arctic ports between 2005-2014: Transport Canada, Howland and Simard unpublished data and Casas-Monroy *et al.* (2015). Vessels were of both domestic (N= 75) and international (N= 178) origin and mainly included bulk carriers and, merchant vessels, but also passenger ships and tugboats. Ballast discharge information was summarized by arrival port, type of BWE, pre-exchange ballast water source, and last port of call for vessel categories. When possible, data on tank-specific pre-exchange ballast water source(s) for each vessel were used for the analysis as ballast water from individual tanks can have different histories and may not originate from the last port of call. When tank-specific information was not available ($N_{Domestic}$= 47 of 75 vessels, $N_{International}$= 68 of 178 vessels), the ballast source was assumed to be from the last port of call. Since this ecological risk assessment is species-specific, only ballast water sources originating from ports where the species of concern was known to be present (either in their native or introduced range) were included in the analyses described below.

Likelihood of arrival

Relative likelihood of arrival for each vessel was estimated as the product of the volume of ballast water discharged (using a correction factor for BWE, see below) at an arrival port and the risk score for vessel transit time (Section *1a* in Figure 15). Individual ballast water sources related to a given port of arrival were then combined to calculate an average likelihood per vessel by pathway (international or domestic), port, year, and species. International vessels were defined as those that operated outside of the Canadian exclusive economic zone and performed mid ocean exchange (MOE) prior to entering Canadian waters. Domestic vessels were defined as those that operated entirely within Canadian waters, and are exempt from submitting ballast water reports or performing BWE. These vessels do not perform BWE, or if they do, it is typically a coastal BWE. It has been shown that, in some cases this practice may decrease the BWE efficacy by increasing diversity of species beyond what was originally taken up in ballast in source ports (McCollin *et al.*, 2008).

A correction factor was applied to the volume discharged according to the type of BWE performed to account for reduction in propagule supply due to ballast water management activities. To this end, ballast water discharge information was categorized according to where BWE was done and if it was performed. When information on the type of BWE was missing, it was assumed that international vessels had performed MOE (N= 5) and that domestic vessels did not perform any ballast water management (N= 15). An exception was the *MV Arctic*, which regularly transits from Quebec City to Raglan Mines in Deception Bay, which was assumed to have performed voluntary coastal BWE as this is normal practice for this vessel (K. Howland, pers. comm.). In cases where a vessel was known to have discharged ballast water in a given port, but the volume was not provided, the volume discharged was assumed to be equivalent to the volume of ballast water on board ($N_{Domestic}$= 11 of 75 vessels, $N_{International}$= 38 of 178 vessels). Following categorization of BWE practices, correction factors were applied to the reported volumes of exchanged ballast water: 0.1 for ships with a saline ballast water source and 0.01 for freshwater source. These values are based on published BWE efficacy rates from total zooplankton abundance after BWE (90% for saline water and 99% for freshwater) (Ruiz & Smith, 2005; Gray *et al.*, 2007) and have been applied in other risk assessments (Chan *et al.*, 2012). When BWE was not performed, no correction factor was applied and the complete volume discharged was considered in the calculation.

The corrected discharged volume was combined with a factor of transit time, which was calculated as the difference between the date the pre-exchange ballast water was taken up at the source port and the date when the ballast water was discharged at the arrival port. Transit time was included to reflect the fact that the faster an organism reaches the destination port, the greater the chance it has of surviving the voyage and establishing a viable population in the new environment (Lockwood *et al.*, 2007). In particular, benthic taxa with a single planktonic life stage (e.g., gastropods and bivalves with planktonic larval stages) are less vulnerable to mortality in transit (Wonham *et al.*, 2001). Details on the planktonic life stages of all case species (normal and maximal larval periods) are available and were taken into consideration in ranking the transit times as low, moderate, and high (scored from 1 to 3, respectively). A low score was assigned when the transit time was longer than the maximum duration known for the larval stage of the species. Conversely, a high score was assigned when the transit time was lower than the average larval stage. Moderate scores were assigned to transit times that were between the average and maximum larval stage duration. In cases where information on the date of ballast water uptake was missing for transits ($N_{Domestic}$= 51 of 75 vessels, $N_{International}$= 46 of 178 vessels), an average of all other transit times was used to complete the missing information. Final values for likelihood of arrival were normalized from 0 to 1 (with 1 being the highest).

Likelihood of survival-establishment

Likelihood of survival and establishment was calculated as the product of habitat suitability for each species assessed and a score for the time of year when ballast water was discharged per vessel (Section *1b* in Figure 15). These values were then combined to calculate an average likelihood of survival-establishment per pathway (international or domestic), port, year, and species. Habitat suitability was estimated based on the predicted suitability of regions for a given case species, resulting from species distribution modelling (SDM) using MaxEnt (Phillips *et al.*, 2006; Elith *et al.*, 2011). To this end, sea surface and bottom temperature, sea surface and bottom salinity, bathymetry and ice coverage were employed as environmental predictors (Goldsmit et al Chapter N°2). The model predictions of habitat suitability were interpreted as likelihood of survival and establishment (Mandrak & Cudmore, 2015) of each species for a given region of the Arctic. To standardize results among organisms, the maximum absolute probability value generated by the model in the region of study was considered to be the highest likelihood of survival-establishment across all three species combined.

Since likelihood of survival and establishment can be expected to vary among seasons (Simard & Hardy, 2004; Simard *et al.*, 2011), the time of the year when the ballast water was discharged was taken into consideration. Low, moderate and high scores were assigned when the ballast water was discharged in winter, spring/autumn, and summer (ranked from 1 to 3, respectively). These ranked scores are based on the idea that the majority of temperate species – those most likely to be introduced – reproduce and recruit during the warmer seasons and would be best able to survive when waters are at their warmest (Simard & Hardy, 2004).

Consequence of occurrence

In this study, the consequence of occurrence is the potential consequences that a species can have if introduced and established in an environment. This section was calculated as the product of the scores of impact and habitat sensitivity of the receiving habitat (Section *2* in Figure 15).

Impact

Impact (Section *2a* in Figure 15) is defined as a measurable change in the ecological state of an invaded ecosystem that can be attributed to the non-indigenous species (Ricciardi *et al.*, 2013). This includes any change in ecological or ecosystem properties. The impact that a species has had elsewhere has been shown to be a good predictor of impact in the new environment (Hayes & Barry, 2008). This risk component was therefore ranked based on documented information in other places where each species is invasive. Web of Science was used to search for documented information on each species. The name of each species was combined with "impact" and "invasion" as key words. The reported effects were divided into four categories and scored using impact rankings adapted from (Hewitt *et al.*, 2006) (Table 8). These categories include: 1) changes in biodiversity, abundance and distribution, 2) changes in interspecific interactions (e.g., competition with native species for resources or space), 3) habitat (changes in the physical environment) and 4) trophic interactions (e.g., predation on native species). These four factors were ranked from low to high (1 to 3 respectively) and summed to produce a score for impact of potential introduction.

Table 8: Categories for ranking impact of non-indigenous species. Modified from Hewitt *et al.* (2006).

	Low	**Moderate**	**High**
Biodiversity, abundance and distribution impact	Reduction in species richness and composition are not readily detectable	Loss of one species. Small reduction of species richness	Likely to cause local extinction. Loss of two or more species
Interspecific interactions	No inter-relationship changes	One kind of inter-relationship affected.	Two or more kinds of inter-relationship affected.
Habitat impact	No significant changes to habitat types	Changes in habitat types and the habitat can be easily recovered	Significant affected habitat area. Significant changes to habitat types
Trophic interactions impact	No significant changes in trophic level species composition. No change in relative abundance of trophic levels (biomass)	Minor changes in trophic interactions	Significant change in relative abundance of trophic levels and reduction of population abundances for top predator species and primary producer species.

Habitat sensitivity

The habitat sensitivity (Section *2b* in Figure 15) criterion was used to include inherent variation in how susceptible receiving areas could be impacted by the introduction of the novel species included in the analysis. Certain areas have been identified as biologically important in the Canadian Arctic, and this information was used to develop a proxy for habitat sensitivity. To this end, information on Ecologically and Biologically Significant Areas (EBSAs, Kenchigton *et al.*, 2011) was used to determine the extent to which ports were in areas identified as possessing key ecological and biological attributes (Kenchington *et al.*, 2011). In addition, more detailed information on certain species groups was also incorporated into the index, including: 1) overlapping species (4 or more overlapping species), 2) areas of high biological importance (highly productive areas due to particular conditions), and 3) hot spots and areas of special interest (areas of high diversity and/or high biomass) (Stephenson & Hartwig, 2010). Although this latter data set is biased toward harvested species, it was thought to be the best available proxy for areas of particular biological importance that could be more sensitive to the arrival of introduced species. To rank ports for habitat sensitivity, each was evaluated to determine the degree to which it overlaps with the spatial distribution of these four variables (EBSA, overlapping species, high biological importance and hot spots). Ports that overlapped with one, two to three, or four sensitivity variables were considered to have low, moderate, and high habitat sensitivity, and were assigned scores from 1 to 3, respectively.

Overall risk

All components described above were combined to evaluate overall risk as shown in Figure 15. Prior to determining overall risk, the likelihood of introduction and the consequence of occurrence were normalized from 0 to 1, using the minimum and maximum values across all three species combined, to standardize results among organisms and ports.

The normalized values for these two risk components were combined in a risk matrix depicted using a gradient approach to provide the overall risk (Mandrak *et al.*, 2012). Risk matrices were constructed for each species by arrival port and year, for both domestic and international transits associated with vessel discharges. The use of this gradient approach enables illustration of the continuous nature of overall risk both spatially (ports) and temporally (years) along the gradients of likelihood of introduction and consequence of occurrence for each species (Mandrak *et al.*, 2012).

Uncertainty

The strength of a risk assessment is dependent on the uncertainty associated with the data (Mandrak *et al.*, 2012) and must be explicitly considered for each step of the risk assessment based on the extent of available information and gaps. Three types of uncertainty exist: stochastic, imperfect knowledge, and human error. In this study, the greatest uncertainty affecting the assessment was imperfect knowledge. Thus, both the quality and quantity of data available to assess probability of introduction and magnitude of consequences were incorporated in uncertainty as recommended by Mandrak and Cudmore

(2015). Uncertainty was considered in each step of the risk assessment according to the availability and kind of information used following a modified approach from Therriault *et al.* (2008). Uncertainty was considered high when limited scientific information was available. In contrast, it was considered low when the analysis was based on substantial scientific information. It was also considered low when quantitative methods, such as the habitat suitability modelling used to calculate the likelihood of survival/establishment, were used in the risk assessment. Uncertainty was considered moderate when there was intermediate level of information. Overall uncertainty was considered to be equivalent to the highest uncertainty associated with any variables used in the analysis (Mandrak *et al.*, 2012).

RESULTS

Deception Bay received the highest average annual domestic arrivals at 7.5, followed by Churchill with 3.6 and Iqaluit with 2.5 (Table 9). Among international vessels Churchill received the highest average annual arrivals at 16.1 followed by Pond Inlet with 3.5 and Iqaluit with 2.5. Of all domestic ships arriving to Canadian Arctic ports, 93.3% discharged ballast at the ports of arrival, while for international ships it was 70.8% (for a complete list of results see Table 9, and refer to Figure 14 for geographical location of ports). The pre-exchange ballast water source differed from the last visited port for 11.1% of domestic arrivals and 31.1% of international arrivals.

Ports with highest domestic and international average annual arrivals did not coincide with the ports receiving the highest vessel-specific corrected volumes of ballast water discharge. For domestic arrivals, Deception Bay received the highest volume/vessel (6140.5 ± 2542.9 MT/year), followed by Churchill (5624.9 ± 6356.7 MT/year) and Aupaluk and Broughton Island (3971 MT/year). For international arrivals, Cape Dyer received the highest volume/vessel (3971 MT/year), followed by Churchill (961.2 ± 646.3 MT/year) and Deception Bay (390.9 ± 637.4 MT/year). These results reflect that there were ports that received a lower number of arrivals, but the mean ballast water discharged/vessel was higher than other ports with a higher number of arrivals (e.g., Deception Bay had a lower number of arrivals per year than Iqaluit and Pond Inlet, but the amount of ballast water discharged/vessel for international arrivals was higher).

Table 9: Number of domestic and international transits with information on the corrected ballast water discharged. Ports with highest average of arrivals and average vessel-specific quantities of corrected ballast water discharged are highlighted in bold. Next to the name of each port, shown as superscript, is the reference number of that port in Figure 14. All information included in this table is according to the data that was found available during the years 2005-2014 for the used data sources: Transport Canada, Howland and Simard unpublished and Casas-Monroy *et al*. (2015).

Domestic arrival ports	Year of arrival	N° of arrivals per year	N° of vessels that discharged ballast water	N° of vessels that did not discharge ballast water	Mean (±SD) corrected ballast water discharged/vessel (MT)
Aupaluk[20]	2005	1	1	0	3971 (0)
	Port mean/year	1	1	0	**3971 (0)**
Broughton Island[9]	2005	1	1	0	3971 (0)
	Port mean/year	1	1	0	**3971 (0)**
Chesterfield[33]	2007	1	0	1	0
	Port mean/year	1	0	1	0
Churchill[30]	2005	4	4	0	11257.3 (7844.7)
	2006	7	7	0	1486.6 (933.6)
	2007	1	1	0	160.7 (0)
	2013	3	3	0	10736.8 (3534.7)
	2014	3	3	0	4480.5 (5119.6)
	Port mean/year	**3.6**	3.6	0	**5624.9 (6356.7)**
Clyde River[6]	2010	1	0	1	0
	Port mean/year	1	0	1	0
Deception Bay[23]	2005	6	6	0	10253 (0)
	2006	6	6	0	10253 (0)
	2007	7	4	3	7542.1 (4161.9)
	2008	10	10	0	9273.6 (2042.8)
	2013	10	10	0	82633.9 (2010)
	2014	6	6	0	8787.2 (1197.1)
	Port mean/year	**7.5**	7	0.5	**6140.5 (2542.9)**
Inukjuak[28]	2005	1	1	0	3384 (0)
	Port mean/year	1	1	0	3384 (0)
Iqaluit[14]	2005	3	3	0	3775.3 (276.7)
	2006	2	2	0	3365.5 (605.5)
	Port mean/year	**2.5**	2.5	0	3611.4 (482.6)
Kuujjuaraapik[29]	2005	1	1	0	6.9 (0)
	2007	1	1	0	3384 (0)
	Port mean/year	1	1	0	1695.5 (1688.6)
International arrival ports	**Year of arrival**	**N° of arrivals per year**	**N° of vessels that discharged ballast water**	**N° of vessels that did not discharge ballast water**	**Mean (±SD) corrected ballast water discharged/vessel (MT)**
Broughton Island[9]	2010	1	0	1	0
	Port mean/year	1	0	1	0
Cape Dyer[10]	2007	1	1	0	3971 (0)
	Port mean/year	1	1	0	**3971 (0)**
Chesterfield[33]	2010	1	0	1	0

	Port mean/year	1	0	1	0
Churchill[30]	2005	12	12	0	632.2 (480.3)
	2006	12	10	2	1343 (1023.5)
	2007	21	18	3	933.7 (507.8)
	2008	18	17	1	936.9 (625.5)
	2009	17	17	0	569.4 (368.9)
	2010	22	20	2	988.5 (472.9)
	2013	14	14	0	1222.1 (880.3)
	2014	13	13	0	880.3 (663.7)
	Port mean/year	**16.1**	15.1	1	**961.2 (646.3)**
Clyde River[6]	2010	1	0	1	0
	Port mean/year	1	0	1	0
Deception Bay[23]	2007	2	1	1	1494.6 (0)
	2008	1	0	1	0
	2009	2	1	1	0.54 (0.54)
	2010	1	0	1	0
	2011	1	1	0	23.4 (0)
	2013	1	1	0	45.1
	Port mean/year	1.3	0.7	0.7	**390.9 (637.4)**
Iqaluit[14]	2007	4	0	4	0
	2008	3	0	3	0
	2009	1	0	1	0
	2010	2	0	2	0
	Port mean/year	**2.5**	0	2.5	0
Kuujjuak[18]	2010	1	0	1	0
	Port mean	1	0	1	0
Pangnirtung[11]	2008	1	0	1	0
	2009	2	0	2	0
	Port mean/year	1.5	0	1.5	0
Pond Inlet[5]	2006	2	0	2	0
	2008	4	0	4	0
	2009	3	0	3	0
	2010	5	0	5	0
	Port mean/year	**3.5**	0	3.5	0
Rankin Inlet[32]	2009	1	0	1	0
	Port mean/year	1	0	1	0
Resolute Bay[2]	2008	1	0	1	0
	Port mean/year	1	0	1	0
Tuktoyaktuk[1]	2008	4	0	4	0
	2009	2	0	2	0
	2010	1	0	1	0
	Port mean/year	2.3	0	2.3	0

Likelihood of introduction

Likelihood of arrival

Four ports of arrival received vessels with domestic ballast water originating from regions where both the periwinkle *L. littorea* and the soft shell clam *M. arenaria* were present (Figure 16, *a* and *c*). Among these, Deception Bay (years 2005, 2006, 2008, 2013 and 2014) and Churchill (year 2005) had the highest annual likelihood of arrival per vessel for both species (Table 10). Nine ports of arrival received vessels with international ballast water originating from regions where *L. littorea* was present, while for *M. arenaria* the number of ports was ten (Figure 16, *b* and *d*). For both species, Churchill had the highest annual likelihood of arrival per international vessel when compared to other ports. Nevertheless, these likelihoods can be considered low for all years (2005 to 2014) since the maximum likelihood was 0.29 on a scale from 0 to 1 (Table 10). For all the other ports receiving international vessels, likelihoods of arrival were zero or close to zero since low quantities of ballast water were discharged or no discharge at all was associated with ballast water coming from places where these species are known to occur (Table 10). In the case of the red king crab *P. camtschaticus*, only the port of Tuktoyaktuk is connected to an international port where the species is present (Table 10, Figure 16*e*). The likelihood of arrival for this species through international ballast water is zero since discharge of ballast water was null. (See Appendix VI for complete information on ballast water discharged per vessel at each port per pathway and species assessed). Uncertainty in this section was considered to be moderate due to the assumptions that needed to be made to complete the database of shipping arrivals.

Likelihood of survival-establishment

The likelihood of survival and establishment of species based on SDM under current environmental conditions is shown in Figure 17. For *L. littorea* and *M. arenaria,* even though the probabilities are low, there are many coastal areas where the habitat is suitable. Only a few ports, including Resolute Bay and Pond Inlet, are situated where the habitat is unsuitable. In contrast, habitat suitability for *P. camtschaticus* is generally much higher and much more extended throughout the Canadian Arctic; however, currently there is only one potential port of arrival. Uncertainty in this section was considered to be low given that it is based on substantial information and proven quantitative methodology.

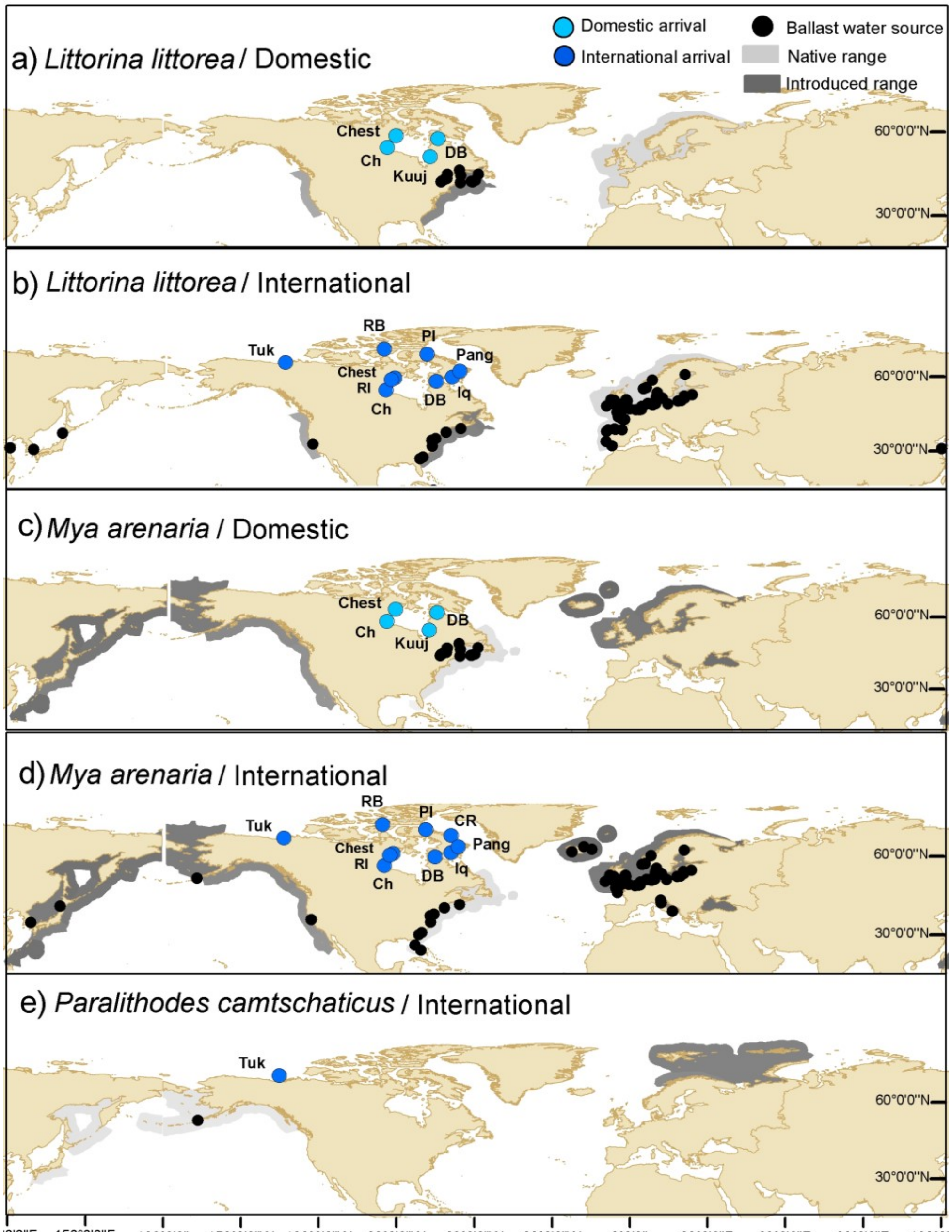


Figure 16: Ports of arrival for the Canadian Arctic coming from regions were the species assessed are present: a) domestic arrivals *Littorina littorea*, b) international arrivals *Littorina littorea*, c) domestic arrivals *Mya arenaria*, d) international arrivals *Mya arenaria*, e) international arrivals *Paralithodes camtschaticus*. Port names are shown as the following: Chesterfield (Chest), Churchill (Ch), Clyde River (CR), Deception Bay (DB), Iqaluit (Iq), Kuujjuaraapik (Kuuj), Pond Inlet (PI), Resolute Bay (RB), Rankin Inlet (RI), Tuktoyaktuk (Tuk).

Table 10: Likelihood of arrival per port and year according to species assessed and pathway. Values represent normalized annual average likelihoods per vessel. Values vary from 0 to 1, with 1 being the highest likelihood of arrival.

Port	Year	*Littorina littorea*		*Mya arenaria*		*Paralithodes camtschaticus*
		Domestic	**International**	**Domestic**	**International**	**International**
Chesterfield	**2007**	0		0		
	2010		0		0	
Churchill	**2005**	1	0.15	0.67	0.14	
	2006		0.29		0.29	
	2007		0.17	0.01	0.16	
	2008		0.21		0.20	
	2009		0.16		0.18	
	2010		0.14		0.17	
	2013		0.26		0.24	
	2014	0.15	0.17	0.15	0.14	
Clyde River	**2010**				0	
Deception Bay	**2005**	0.90		0.60		
	2006	0.90		0.60		
	2007	0.30	0.05	0.20	0.15	
	2008	0.81	0	0.60	0	
	2009		0		0	
	2010		0		0	
	2011		0		0	
	2013	0.73	0	0.71	0	
	2014	0.77		0.59		
Iqaluit	**2007**		0		0	
	2008				0	
	2009		0		0	
	2010		0		0	
Kuujjuaraapik	**2005**	0		0		
Pangnirtung	**2009**		0		0	
Pond Inlet	**2010**		0		0	
Rankin Inlet	**2009**		0		0	
Resolute Bay	**2008**		0		0	
Tuktoyaktuk	**2008**				0	0
	2009		0		0	

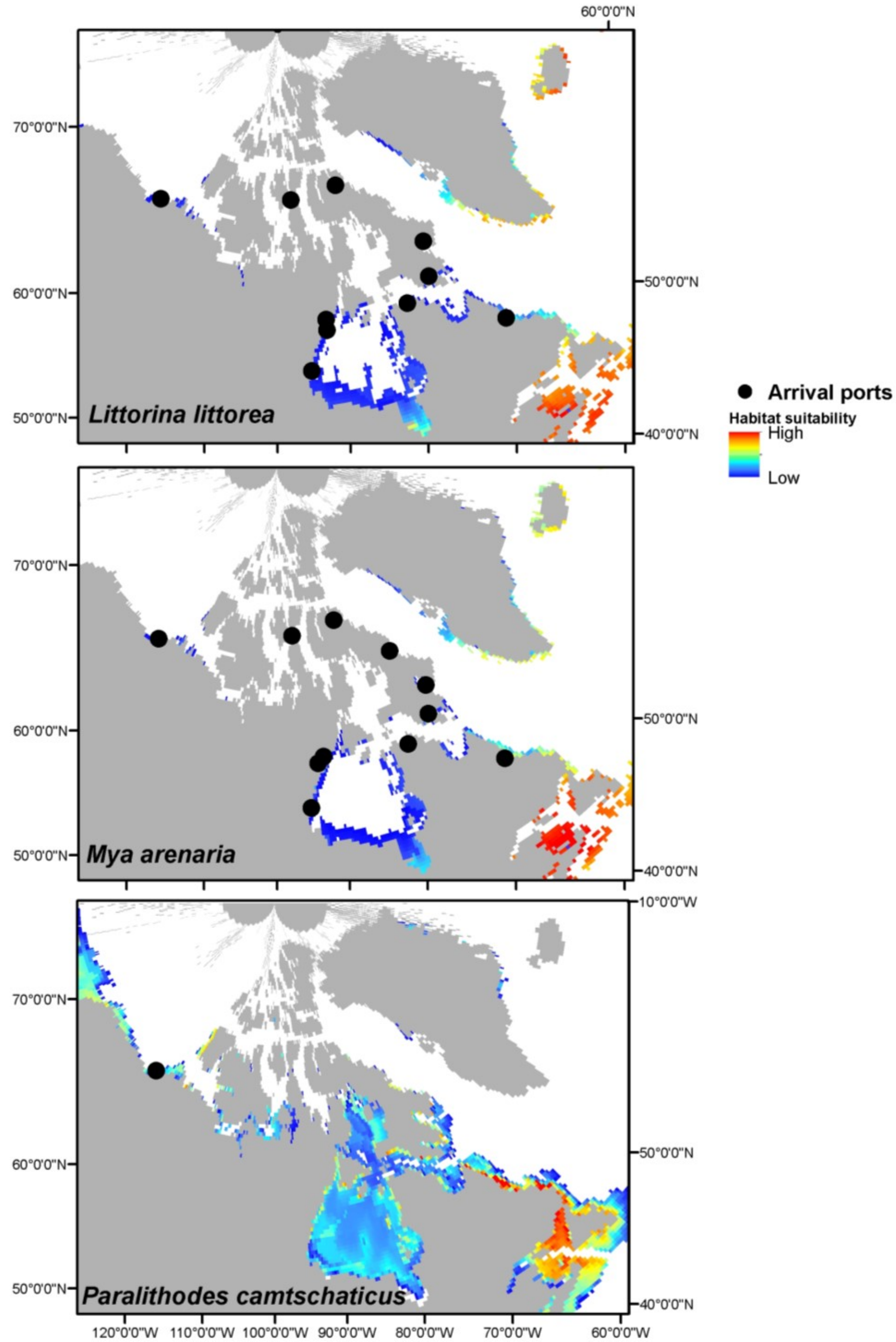


Figure 17: Likelihood of survival and establishment based on habitat suitability for *Littorina littorea*, *Mya arenaria* and *Paralithodes camtschaticus* under current environmental conditions. All colored areas are to some extent suitable for the species (modified from Goldsmit *et al*., Chapter 2).

Consequence of occurrence

Impact

Evidence for impacts of the species assessed in this study is given in Table 11. All three species have a history of known effects in other environments in all four impact categories. The scores of potential impact varied from moderate to high, depending on the species and the category, with *P. camtschaticus* having the highest overall combined score for impact. Uncertainty was considered to be low given the substantial scientific information available.

Table 11: Potential impact of the species assessed according to known effects in invaded environments.

Species	Biodiversity, abundance and distribution	Interspecific interactions	Habitat	Trophic interactions	References
Littorina littorea	**Moderate**	**High**	**High**	**Moderate**	Brenchley and Carlton (1983), Bertness (1984), Petraitis (1987), Carlton (1999), Eastwood *et al.* (2007), Tyrrell *et al.* (2008), Chang *et al.* (2011), Harley *et al.* (2013)
	-Changes in abundance of natives gastropods -Changes in abundance and biodiversity in plants and other animals	-Resource competition -Displace of native species -Niche shifts in native gastropods	-Alters distribution and abundance of algae, converting soft sediment to hard substrates through grazing -Changes in habitat physical conditions -Changes in the rocky intertidal community structure	-Grazing activity can change the intertidal ecosystem	
Mya arenaria	**Moderate**	**Moderate**	**High**	**Moderate**	Leppäkoski (1991), Petersen *et al.* (2008), Crocetta and Turolla (2011)
	-Changes in phytoplankton composition and zooplankton abundance -Reduction in biomass and coverage of benthic vegetation	-Outcompetes with native bivalves	-Affects composition and granulometric structure of shallow water and sea shore deposits -Its shells form a secondary hard substrate available for associated species in mobile bottoms -Change in regime shift: from pelagic turnover to benthic pelagic coupling -Changes in water transparency, increasing plant coverage	-Changes in benthic algae can affect herbivorous seabirds	

Species	Biodiversity, abundance and distribution	Interspecific interactions	Habitat	Trophic interactions	References
Paralithodes camtschaticus	**High**	**High**	**High**	**High**	Orlov and Ivanov (1978), Tilman (1999), Veldhuizen and Stanish (1999), Gudimov *et al.* (2003), Haugan (2004), Pavlova *et al.* (2004), Anisimova *et al.* (2005), Jørgensen (2005), Gilbey *et al.* (2008), Dvoretsky and Dvoretsky (2009), Britayev *et al.* (2010), Falk-Petersen *et al.* (2011), Oug *et al.* (2011),
	-Changes in biodiversity, reduced benthic biomass and diversity -It can eliminate up to 15% of the coastal population of sea urchin -Reduction in soft-bottom communities in number of large individuals. Changes in dominance by small individuals	-Competition with fish such as haddock, cod, wolfish and Atlantic cod (overlap in diet)	-Modify bottom communities -Changes in physical appearance in benthic communities and alteration in community structure -The crabs are also physical structures themselves and may represent new habitats that could allow increased biodiversity (13 different species found as fouling on crabs carapace) -Reduce stability of local habitats through burrowing activity	-It is a large general predator. It can consume on 100 different species (invertebrates, algae and fish remnants): -Impact in bottom native communities -Affect native population of scallops, eggs of lumpsucker, sea urchins, capelin through direct predation	

Habitat sensitivity

Ports that received any domestic or international ships in the study period were evaluated for habitat sensitivity. The ports with highest sensitivity were Deception Bay, Pangnirtung and Resolute Bay (Figure 18). All other ports that received domestic or international vessels had moderate sensitivity. None of the ports considered in this section of the study were characterized as having low habitat sensitivity. Uncertainty for habitat sensitivity was considered to be low given that the information used in this section was based on substantial published scientific information for the study region.

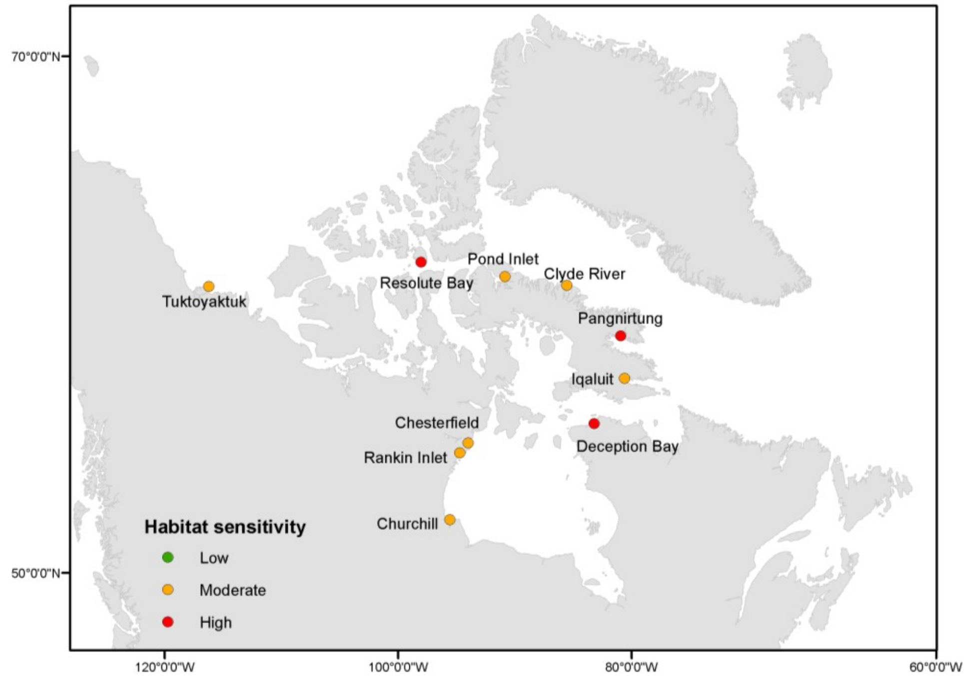


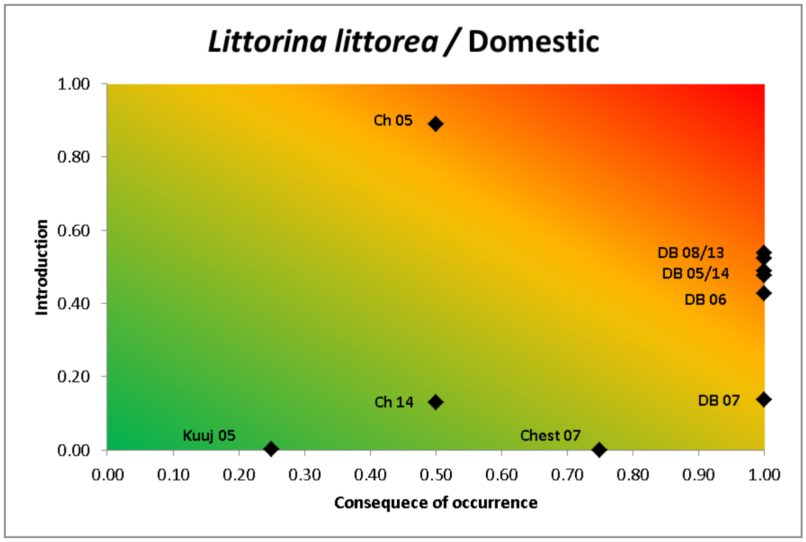
Figure 18: Ports showing locations and habitat sensitivity according to the overlap of sensitivity variables.

Overall risk

Relative likelihood of introduction was combined with consequence of occurrence in gradient matrices to illustrate overall vessel-specific risk for each species, port and year for both domestic and international arrivals (Figure 19 and Figure 20). Generally, overall risk levels varied greatly among ports, years, species and pathways. In a few cases, such as domestic vessels arriving at Deception Bay, there was a trend for increasing risk through time. In general, domestic discharge events posed a higher relative overall risk than did international discharges. In particular, vessel discharges in the port of Deception Bay posed the highest overall risk for domestic arrivals, followed by the port of Churchill; while for international arrivals no particular port appeared to be at highest relative overall risk.

The patterns of overall risk associated with discharges from domestic vessels were similar for *L. littorea* and *M. arenaria*. For the periwinkle *L. littorea*, risk was variable for Churchill, with moderate to high overall risk in 2005, and low to moderate risk in 2014. In contrast, overall risk for Deception Bay was relatively stable through time, at moderate to high from 2005 to 2014; although it was low to moderate in 2007 (Figure 19*a*). For international vessels, most of the ports receiving traffic from regions where the species is present had low relative overall risk associated with vessel discharges, with the exception of Deception Bay in 2007, where relative overall risk was low to moderate (Figure 19*b*). For the soft shell clam *M. arenaria*, domestic vessels arriving at Churchill varied between years, ranging from low to moderate risk. Relative risk to Deception Bay generally increased from moderate (2005-2007) to high (2008-2014) (Figure 20*a*). For international arrivals, most ports showed a low relative overall risk, with the exception of Resolute Bay, which varied from low to moderate (Figure 20*b*). Although some of these ports could be highly impacted, the likelihood of introduction for *M. arenaria* is generally low for international vessels, resulting in decreased overall risk. For red king crab *P. camtschaticus*, only one port in the Canadian Arctic was connected to a region where this species is present and it only received one international ship, on a single occasion, which did not discharge ballast. Thus, no risk matrix is shown for this species. The overall risk for the red king crab was low for Tuktoyaktuk, mainly due to a low likelihood of arrival. However, this species would be expected to have a high consequence of occurrence if introduced.

The uncertainty associated with likelihood of introduction was moderate (combination of moderate uncertainty for likelihood of arrival and low uncertainty for likelihood of survival/establishment), and low for consequence of occurrence (combination of low uncertainty for impact and low uncertainty for habitat sensitivity). Hence, the overall uncertainty was moderate since it is based on the combination of moderate uncertainty for likelihood of introduction and low uncertainty for consequence of occurrence.



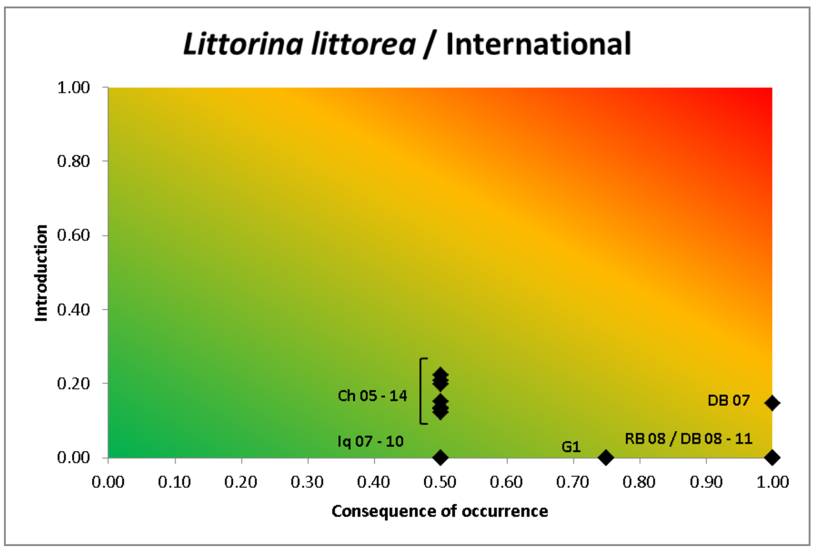
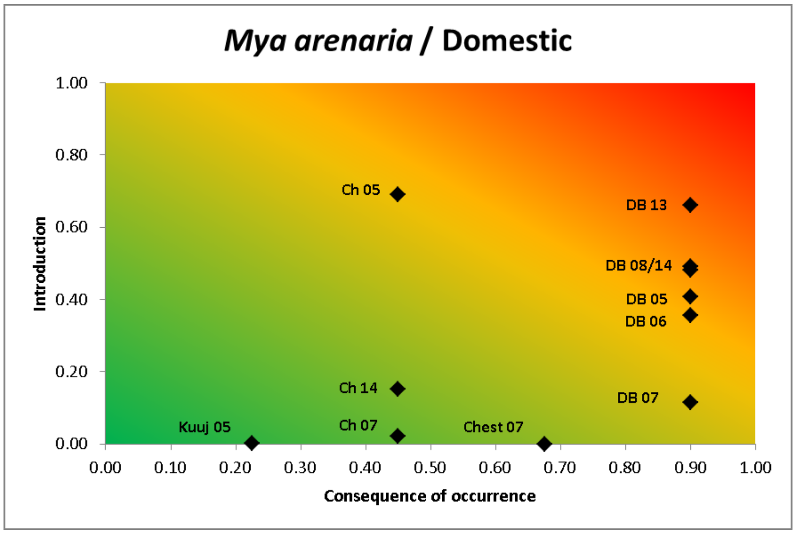


Figure 19: Risk matrix depicted as a gradient showing the differences between ports and years for *Littorina littorea* for a) domestic and b) international vessels. Colors represent overall risk associated with vessel discharges: Low (green), moderate (yellow) and high (red). Port names are shown as the following: Chesterfield (Chest), Churchill (Ch), Deception Bay (DB), Iqaluit (Iq), Kuujjuaraapik (Kuuj), Resolute Bay (RB). G1 is a group of port/years having low risk and being all close to each other. G1 includes: Chesterfield 2010, Pond Inlet 2010, Rankin Inlet 2009 and Tuktoyaktuk 2009.



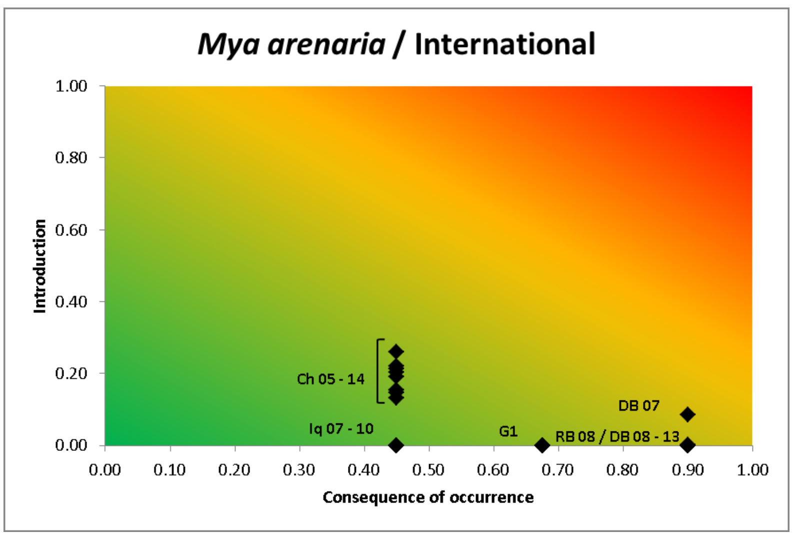


Figure 20: Risk matrix depicted as a gradient showing the differences between ports and years for *Mya arenaria* for a) domestic and b) international vessels. Colors represent overall risk associated with vessel discharges: Low (green), moderate (yellow) and high (red). Port names are shown as the following: Chesterfield (Chest), Churchill (Ch), Deception Bay (DB), Iqaluit (Iq), Kuujjuaraapik (Kuuj), Resolute Bay (RB). G1 is a group of port/years having low risk and being all close to each other. G1 includes: Chesterfield 2010, Clyde River 2010, Pond Inlet 2010, Rankin Inlet 2009 and Tuktoyaktuk 2008 and 2009.

DISCUSSION

This relative risk assessment provides information on the potential risk of introduction and impact for three species that are not, to our knowledge, currently present in the Canadian Arctic, but for which there is likely suitable habitat for their survival and establishment in the region. The methodology used in the present study is unique in that it considers ballast water sources and the distribution of invasive species (e.g., the potential availability of invasive species propagules in ballast water sources). Moreover, it evaluates the relative risk of each port, each year, for each species considered, thus allowing for ecological risk assessment at the species-level. The results show that ports in the Canadian Arctic have likely been exposed to propagules of invasive species established in connected ports, especially via domestic vessels. Although the current likelihoods of introduction for the species considered in this study are generally low, it is important to note that the consequence of occurrence of their establishment ranges from moderate to high for most of the ports. Thus, if vessel-specific ballast water discharges increase in the future, so will the relative overall risk. This is a plausible scenario given that shipping activity in the Canadian Arctic is expected to increase in the future due to the opening of seasonal trading routes through the North West Passage and increasing resource exploitation in the region (Smith & Stephenson, 2013; Gavrilchuk & Lesage, 2014). This scenario could be also influenced by the projected increase in the habitat suitability of the species in the region, as shown in Chapter 2.

Ballast water discharges were shown to be temporally and spatially variable such that potential for introduction is not uniform among Canadian Arctic ports, in agreement with the work by Chan *et al.* (2013). On the other hand, potential impacts vary by species and location. Thus, overall risk of vessel discharges may fluctuate according to location, time and species when all factors are considered. In general, the Hudson Bay Complex can be considered to be at higher relative risk compared to the other regions in the Canadian Arctic. This can be explained by the fact that this region receives a greater proportion of vessels coming from regions where the species of concern are present, combined with the type of exchange performed, and given that majority of vessels' destination ports are situated in this area. Moreover, there is evidence that these ports have a higher environmental similarity with a large number of their connected ports (Chan *et al.*, 2012). In particular, vessel discharges in Deception Bay were found to pose greater overall risk in some years for some species, relative to other ports receiving a higher number of vessel discharges, such as Churchill, because of the unique combination of ballast history/discharges and consequence of occurrence.

Management actions vary by vessel origin. International vessels are required to perform MOE of ballast water prior to entering Canadian waters. In contrast, domestic vessels operating within Canadian waters are exempt from ballast water exchange requirements, although some do so on a voluntary basis. Depending on the source port, domestic vessels that do not conduct BWE may transport large volumes of ballast from other marine regions of Canada that may include some of the invasive species considered in this study. Discharge of un-exchanged ballast water can thus represent a higher actual likelihood of introduction (DiBacco *et al.*, 2012). However, domestic vessels originating from freshwater ports and undertaking voluntary ballast water exchange in brackish/saline coastal waters may also inadvertently increase the probability of introducing propagules of the marine species assessed in this study, which would not have otherwise been present in the original freshwater ballast. Hence, risk is expected to vary among ports as a function of source, discharge, and treatment of ballast water, in agreement with Verling *et al.* (2005) and Cordell *et al.* (2009). However, successful invasion may require multiple introductions (Lockwood *et al.*, 2005) and the volume and location of ballast water release might be more important for introduction success than the number of organisms contained in the released water (Drake *et al.*, 2005). Yet, the number of propagules released in a given event may also be important, since the higher the number of individuals released, the more likely some will survive stochastic events (Lockwood *et al.*, 2007). In any case, the correct combination of suitable environmental conditions need to be adequate for the establishment and growth of the individuals to occur (Carlton, 1996a). Alternative approaches for ballast water management such as release of smaller volumes at multiple independent locations instead of the current practice of larger volumes into a single enclosed port region have been proposed as a way to decrease the risk of all propagules arriving to the same port and establishing (Drake *et al.*, 2005).

Ballast water release and hull fouling are thought to be the most important invasion vectors for aquatic organisms (Ruiz *et al.*, 1997; Ruiz *et al.*, 2015). Therefore, accurate ship history is of great importance in assessing risk of ballast discharge. Importantly, distinguishing between the last port of call and the ballast water source, as was done in this risk assessment, should logically increase the accuracy of assessing the risk of any given discharge event and, when available, this information should always be used. This is particularly important when assessing the risk of a given species for which distributional data is available, as it provides a better estimate of risk for species that, if introduced, may have dramatic consequences (David *et al.*, 2015). If ballast origin is incorrectly attributed, results in this type of risk assessment may be misleading. To our knowledge, no other pathway risk assessment studies have considered ballast water source differently from the source port. Another important component of ship history is transit time (time since ballast uptake until it is discharged) which impacts biological communities in ballast water (Briski *et al.*, 2012). Natural mortality in ballast water tanks has been observed (Simard *et al.*, 2011) and, all else being equal, proximity of donor region and ballast water age will affect propagule condition (Lockwood *et al.*, 2007), such that propagules that spend less time in ballast will be more able to survive transit and establish. Despite propagule mortality due to ballast water treatment, degrading conditions, and natural senescence, some individuals may continue to survive transits, as shown by sampling organisms in ballast water upon arrival in receiving ports (Lockwood *et al.*, 2007). In particular, benthic invertebrates that spend only part of their lives as plankton (e.g., gastropods and bivalves) appear to be less vulnerable to mortality *en route* (Wonham *et al.*, 2001). Thus, although it is not possible to predict when arrivals might occur, a precautionary approach is recommended given the possibility of propagules being discharged in the recipient port (David *et al.*, 2015).

Predicting a species establishment in an environment needs to be carefully evaluated by considering life stages, seasonal variations, and abiotic tolerances (Barry *et al.*, 2008; David *et al.*, 2015). The present risk assessment took all these factors into consideration in the overall risk calculation by including transit time relative to the length of planktonic stage for each species, and the season when the ballast water was discharged. These factors, when combined with the use of predicted habitat suitability, should improve the preciseness of risk assessments allowing analyses to be done at a species level. The present study assessed the overall risk of two mollusks (*Littorina littorea* and *Mya arenaria*) and one crustacean (*Paralithodes camtschaticus*). A common characteristic of these species is that they all include a long-lived feeding planktonic larval period (planktotrophic). Larval ecology (i.e., short-lived non-feeding larvae, called lecitotrophic, versus planktotrophic larvae) may influence how dispersal rates vary for organisms with different reproductive strategies (Johannesson, 1988). The risk of introduction may be affected by the fact that some species can delay their metamorphosis in the absence of suitable substrate for settlement, thus extending their planktonic larval phase from weeks to months (Thorson, 1950). This may increase the risk of introduction as such larvae may survive extended periods by feeding in the water column. In addition, MOE is not always effective for certain species, including *L. littorea* and *M. arenaria* (Briski *et al.*, 2012). For these two species in the current risk assessment, the overall risk was higher for discharges from domestic rather than international arrivals. Given that both are presently distributed in regions where the coastal exchange of ballast water of domestic vessels was performed, the management action (ballast water exchange) in this case is likely increasing the risk. Although ballast water exchange logically reduces the risk of introduction of new species, in some cases, the efficacy of ballast water exchange as a mitigation strategy is questionable, as pointed out by other authors (Carlton, 1985; Gollasch *et al.*, 2000; Carlton, 2001; Carver & Mallet, 2002). In contrast, the likelihood of *P. camtschaticus* arrival by domestic transits was null and was low for international transits. However, trans-Arctic exchange of species is expected in the future (Renaud *et al.*, 2015) and environmental niche modelling suggests that most Canadian Arctic regions are suitable for this species

(Goldsmit *et al.* Chapter 2). Given this, the risk of introduction could be increased by marine transportation or from natural dispersion via currents or migration. There is evidence that some shallow water organisms have been able to extend their ranges from the Bering Sea to the Atlantic as a results of warmer Arctic conditions (Vermeij & Roopnarine, 2008).

In general, known consequences of a species in one location are good predictors of consequences in new introduced ranges and this information is commonly used in risk assessments (Bomford, 2008; Hayes & Barry, 2008). The most documented consequences include declines in native populations, altered nutrient cycling, food web alterations, and physical habitat changes. There is no certain way to precisely predict the impact that a given non-indigenous species will cause in a new environment unless it becomes established (Harley *et al.*, 2013; David *et al.*, 2015). The consequence of occurrence assessed in the present study included the combination of the known consequences of each species when it had established elsewhere and sensitivity of the receiving habitat. Impacts are inherent to the species, while habitat sensitivity is inherent to the port. The latter is essential to include in these types of assessment as it is reasoned that the severity of consequences will also be a function of receiving habitat characteristics. In the present study, most of the ports showed moderate to high potential consequence of occurrence. If impacts and habitat sensitivity remain constant, the overall risk will increase as the likelihood of introduction increases, varying with ballast water source and species assessed. This demonstrates the importance of preventing the introduction of new species and highlights the need for good management actions and preventive measures for ballast water management in this region.

The ecological risk assessment protocol proposed in the present study allowed for assessment of ports through time and enabled comparison between species and shipping pathways. It must be noted that the assessment is relative, meaning that overall risk depends on the ports and species assessed. One component that is missing, and is normally included in the calculation of introduction likelihood (Mandrak *et al.*, 2012), is spread from the initial introduction location (species dispersion after establishment). Spread has an important influence on introduction likelihood, as has been shown in other risk assessments analyses (Therriault *et al.*, 2008). Spread was not included in the present study since much of the required information, including high resolution data on oceanographic currents and ice-ocean modelling systems, is not available for nearshore coastal areas of the Arctic where ports are located. A limitation of this relative risk assessment is that assumptions were made on missing ballast information, although the best available information was used. A particular effort was made to gather detailed information on number of arrivals, ballast water sources, transit times, type of exchange performed and volume of ballast water discharged. A further limitation of this study is that other vectors directly related to shipping such as biofouling and ballast sediments were not assessed. Thus, the actual overall risk for a species may be underestimated if it is associated with hull fouling (Williams *et al.*, 2013), hull refuges, including sea chests (Frey *et al.*, 2014). Or it may be also underestimated when associated with ballast sediments, which have been shown to include viable resting stages of many species with the potential of being released during de-ballasting in the receiving port due to resuspension (Villac *et al.*, 2000; Casas-Monroy *et al.*, 2011; Villac & Kaczmarska, 2011). Indeed, Chan *et al.* (2015) suggested that ports in the Canadian Arctic are at greater risk to invasion by hull fouling than they are to ballast-mediated introductions. The whole history of these types of vectors is important to know (not only last port of call) and their importance will depend on the species being assessed and their life histories. The present relative risk assessment was undertaken using both quantitative and qualitative data. Even though the general perception may be that quantitative risk assessments are more robust than qualitative ones, it is important to highlight that the strength of any risk assessment is more dependent on the uncertainty associated with the data used in the analysis (Mandrak *et al.*, 2012). Uncertainty in the present risk assessment was moderate due to missing information in certain components of the overall risk calculation, such as in the likelihood of introduction. Nevertheless, the data used was the most comprehensive available at the time, and, as explained by Gibbs and

Browman (2015), one of the most valuable outcomes of a risk assessment is to identify the knowledge gaps and the data required to quantify risk.

Currently, many countries are developing blacklists (lists of non-native species with presumed invasive potential in the area of interest) (García-de-Lomas & Vilà, 2015). These lists are developed with the aim of preventing introductions of new harmful species and regulating the spread of species that are already present in a given region (Burgiel *et al.*, 2006). Recently, “grey” watch lists, which contain species of potential risk (Genovesi & Shine, 2011) have also been developed. The present ecological risk assessment can provide a starting point to build a grey watch list for the Canadian Arctic. This ecological risk assessment is the first study done for the Canadian Arctic at a species level. Although, only three species were assessed in this particular study, the proposed methodology may be used for any species of interest and provides an ideal tool for assessing the relative risk of potential new introductions in areas that have not yet been invaded. Such information can help guide prevention and management efforts in frontier regions where knowledge is lacking, such as the Canadian Arctic.

ACKNOWLEDGEMENTS

Special thanks to Paul Mudroch from Transport Canada for collaborating completing the shipping database and answering each question and Nathalie Simard from Institut Maurice Lamontagne, Fisheries and Oceans Canada, for her comments also sharing shipping database. We are grateful for funding from the Natural Sciences and Engineering Research Council’s (NSERC) Canadian Aquatic Invasive Species Network (CAISN), the Fisheries and Oceans Canada Aquatic Climate Change Adaptation Service Program (ACCASP), the Nunavut Wildlife Management Board (NWMB) and Quebec-Ocean (Fonds de recherche du Quebec – Nature et technologies (FRQNT)).

APPENDIX VI: BALLAST WATER DISCHARGE IN CANADIAN ARCTIC PORTS

Complete information on ballast water discharged at each Canadian Arctic port considered for each species and pathway assessed. Volumes are given in metric tons (MT). Correction factor for ballast water exchange: No exchange= 1, Mid ocean exchange (MOE) for ships with a saline ballast water source= 0.1, MOE for ships with freshwater ballast water source= 0.01

Species: *Littorina littorea*

Pathway: Domestic vessels

Arrival Date	Arrival Port (Domestic)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	Corrected volume (MT)	BW discharged at port
29/09/2007	Chesterfield	Sydney	Sydney	0	No exchange	1	0	no
07/10/2005	Churchill	Sept Iles	Sept Iles	11397	No exchange	1	11397	yes
29/09/2014	Churchill	Sept Iles	Sept Iles	16764.7	MOE	0.1	1676.47	yes
27/02/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
15/06/2005	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
22/08/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
01/10/2005	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
01/11/2005	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
30/12/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
15/03/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
18/06/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
22/10/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
27/11/2006	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
26/12/2006	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
04/02/2007	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
26/03/2007	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
27/08/2007	Deception Bay	Mulgrave	Mulgrave	0	Coastal	1	0	no
13/09/2007	Deception Bay	Lower Cove	Lower Cove	0	No exchange	1	0	no
23/09/2007	Deception Bay	Lower Cove	Lower Cove	0	No exchange	1	0	no
11/11/2007	Deception Bay	Saint John	Saint John	3653	MOE	0.1	365.3	yes
04/01/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
07/03/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
18/04/2008	Deception Bay	Chicoutimi	Chicoutimi	5712	Coastal	1	5712	yes

Arrival Date	Arrival Port (Domestic)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	Corrected volume (MT)	BW discharged at port
17/06/2008	Deception Bay	Becancour	Becancour	10253	Coastal	1	10253	yes
22/07/2008	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
11/08/2008	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
28/08/2008	Deception Bay	Belledune	Belledune	5000	No exchange	1	5000	yes
15/09/2008	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
11/10/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
19/12/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
15/06/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/06/2013	Deception Bay	Montreal	Montreal	3419.1	Coastal	1	3419.1	yes
20/07/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/08/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
02/09/2013	Deception Bay	Quebec	Quebec	7257	Coastal	1	7257	yes
02/10/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
14/10/2013	Deception Bay	Summerside	Summerside	5671	No exchange	1	5671	yes
18/10/2013	Deception Bay	Quebec	Quebec	4774	Coastal	1	4774	yes
03/11/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
05/12/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
11/01/2014	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
28/02/2014	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/07/2014	Deception Bay	Contrecoeur	Contrecoeur	7363	Coastal	1	7363	yes
23/08/2014	Deception Bay	Quebec	Quebec	9072	Coastal	1	9072	yes
18/09/2014	Deception Bay	Quebec	Quebec	8432	Coastal	1	8432	yes
16/10/2014	Deception Bay	Quebec	Quebec	7350	Coastal	1	7350	yes
21/08/2005	Kuujjuaraapik (Great Whale)	Montreal	Montreal	690	MOE	0.01	6.9	yes

Species: *Littorina littorea*

Pathway: International vessels

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
17/10/2010	Chesterfield	Rotterdam	Antwerp	0	MOE	0.01	0	no
11/08/2005	Churchill	Newport News	Newport News	2779	MOE	0.1	277.9	yes
03/09/2005	Churchill	Greenore	Greenore	9188	MOE	0.1	918.8	yes
11/09/2005	Churchill	Newport News	Newport News	6346	MOE	0.1	634.6	yes

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
18/09/2005	Churchill	Baltimore	Baltimore	10489	MOE	0.1	1048.9	yes
21/09/2005	Churchill	Ijmuiden	Ijmuiden	17656	MOE	0.1	1765.6	yes
28/09/2005	Churchill	Savannah	Savannah	958	MOE	0.1	95.8	yes
06/10/2005	Churchill	Baltimore	Baltimore	5505	MOE	0.1	550.5	yes
20/08/2006	Churchill	Charleston	Charleston	17114	MOE	0.1	1711.4	yes
04/09/2006	Churchill	Belfast	Belfast	4764	MOE	0.1	476.4	yes
04/09/2006	Churchill	Foynes	Belfast	6861	MOE	0.1	686.1	yes
04/09/2006	Churchill	Belfast	Belfast	931	MOE	0.1	93.1	yes
04/09/2006	Churchill	Foynes	Foynes	6852	MOE	0.1	685.2	yes
13/09/2006	Churchill	London	London	11515	MOE	0.01	115.2	yes
14/09/2006	Churchill	Aughinish	Aughinish	0	No exchange	0.1	0	no
27/09/2006	Churchill	Amsterdam	Amsterdam	32901	MOE	0.1	3290.1	yes
11/10/2006	Churchill	Terneuzen	Terneuzen	31358	MOE	0.1	3135.8	yes
13/10/2006	Churchill	Dublin	Falmouth	10087	MOE	0.1	1008.7	yes
15/10/2006	Churchill	Dublin	Dublin	10051	MOE	0.1	1005.1	yes
18/10/2006	Churchill	Gijon	Gijon	0	MOE	0.1	0	no
11/08/2007	Churchill	Hamburg	Hamburg	11397	MOE	0.1	1139.7	yes
14/08/2007	Churchill	Lorient	Lorient	0	MOE	0.1	0	no
22/08/2007	Churchill	Klaipeda	Klaipeda	13466	MOE	0.1	1346.6	yes
27/08/2007	Churchill	Ronnskar	Ronnskar	10680	MOE	0.1	1068	yes
27/08/2007	Churchill	Ronnskar	Skagen	11156	MOE	0.1	1115.6	yes
04/09/2007	Churchill	Antwerp	Antwerp	2696	MOE	0.01	27	yes
04/09/2007	Churchill	Newport	Antwerp	5615	MOE	0.01	56.2	yes
04/09/2007	Churchill	Antwerp	Antwerp	1348	MOE	0.01	13.5	yes
04/09/2007	Churchill	Newport	Newport	5615	MOE	0.01	56.2	yes
25/09/2007	Churchill	Sunndalsora	Sunndalsora	14451	MOE	0.1	1445.1	yes
02/10/2007	Churchill	Bremen	Bremen	10697	MOE	0.01	107	yes
05/10/2007	Churchill	Londonderry	Londonderry	14226	MOE	0.1	1422.6	yes
05/10/2007	Churchill	Liverpool	Londonderry	3228	MOE	0.1	322.8	yes
11/10/2007	Churchill	Dublin	Dublin	6818	MOE	0.1	681.8	yes
11/10/2007	Churchill	Portbury	Portbury	9629	MOE	0.1	962.9	yes
11/10/2007	Churchill	Dublin	Portbury	6818	MOE	0.1	681.8	yes
16/10/2007	Churchill	Tyne	Muuga-Port Of Tallinn	0	MOE	0.01	0	no
08/11/2007	Churchill	Hamburg	Unknown	11397	MOE	0.1	1139.7	yes
04/08/2008	Churchill	Szczecin	Szczecin	27426	MOE	0.1	2742.6	yes
08/08/2008	Churchill	Kaliningrad	Kaliningrad	0	MOE	0.1	0	no

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
13/08/2008	Churchill	Riga	Copenhagen	11627	MOE	0.1	1162.7	yes
13/08/2008	Churchill	Riga	Riga	11624	MOE	0.1	1162.4	yes
21/08/2008	Churchill	Gdynia	Gdynia	7825	MOE	0.1	782.5	yes
21/08/2008	Churchill	Rotterdam	Rotterdam	8398	MOE	0.01	84	yes
31/08/2008	Churchill	Aviles	Aviles	7288	MOE	0.1	728.8	yes
08/09/2008	Churchill	Teesport	Teesport	977	MOE	0.1	97.7	yes
08/09/2008	Churchill	Teesport	Teesport	9188	MOE	0.1	918.8	yes
14/09/2008	Churchill	Amsterdam	Amsterdam	11394	MOE	0.1	1139.4	yes
19/09/2008	Churchill	Ghent	Ghent	10905	MOE	0.01	109.1	yes
19/09/2008	Churchill	Ghent	Ghent	220	MOE	0.01	2.2	yes
30/09/2008	Churchill	Liepaja	Liepaja	372	MOE	0.1	37.2	yes
23/10/2008	Churchill	Sunndalsora	Sunndalsora	11636	MOE	0.1	1163.6	yes
11/08/2009	Churchill	Liepaja	Liepaja	9208	MOE	0.1	920.8	yes
25/08/2009	Churchill	Brest	Portland	5990	MOE	0.1	599	yes
30/08/2009	Churchill	La Coruña	Portland	7188	MOE	0.1	718.8	yes
12/09/2009	Churchill	Ronnskar	Ronnskar	5746	MOE	0.1	574.6	yes
12/09/2009	Churchill	Brunsbüttel	Ronnskar	4338	MOE	0.1	433.8	yes
05/10/2009	Churchill	Lisbon	Lisbon	2494	MOE	0.1	249.4	yes
05/10/2009	Churchill	Lisbon	Lisbon	1058	MOE	0.1	105.8	yes
05/10/2009	Churchill	Leixoes	Lisbon	3986	MOE	0.1	398.6	yes
09/10/2009	Churchill	Vlissingen	Vlissingen	13634	MOE	0.1	1363.4	yes
15/10/2009	Churchill	Bilbao	Rotterdam	5160	MOE	0.1	516	yes
15/10/2009	Churchill	Rotterdam	Rotterdam	2780	MOE	0.01	27.8	yes
03/08/2010	Churchill	Hamburg	Nuuk	0	MOE	0.1	0	no
05/08/2010	Churchill	Klaipeda	Klaipeda	10570	MOE	0.1	1057	yes
12/08/2010	Churchill	Gijon	Gijon	11105	MOE	0.1	1110.5	yes
24/08/2010	Churchill	Newport	Falmouth	9548	MOE	0.01	95.5	yes
24/08/2010	Churchill	Falmouth	Falmouth	880	MOE	0.1	88	yes
26/08/2010	Churchill	Ghent	Ghent	10451	MOE	0.01	104.5	yes
30/08/2010	Churchill	Vlissingen	Vlissingen	7500	MOE	0.1	750	yes
07/09/2010	Churchill	Lisbon	Lisbon	4345	MOE	0.1	434.5	yes
07/09/2010	Churchill	Lisbon	Lisbon	2021	MOE	0.1	202.1	yes
24/09/2010	Churchill	Huelva	Gibraltar	18836	MOE	0.01	188.4	yes
12/10/2010	Churchill	Montoir	Montoir	11110	MOE	0.1	1111	yes
12/10/2010	Churchill	Montoir	Montoir	2426	MOE	0.1	242.6	yes
14/08/2013	Churchill	Sauda	Sauda	27462	MOE	0.1	2746.2	yes

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
30/09/2013	Churchill	Antwerp	Antwerp	16333.4	MOE	0.01	163.3	yes
18/10/2013	Churchill	Ghent	Ghent	13759.5	MOE	0.01	137.6	yes
31/10/2013	Churchill	Karmoy	Karmoy	10285	MOE	0.1	1028.5	yes
03/11/2013	Churchill	Sauda	Sauda	2731.6	MOE	0.1	273.2	yes
04/08/2014	Churchill	Lisbon	Lisbon	15628.6	MOE	0.1	1562.9	yes
09/08/2014	Churchill	Dunkirk	Dunkirk	14713.9	MOE	0.1	1471.4	yes
31/08/2014	Churchill	Tyne	Tyne	14358.6	MOE	0.01	143.6	yes
07/09/2014	Churchill	Ghent	Ghent	13277	MOE	0.01	132.8	yes
19/09/2014	Churchill	Rotterdam	Rotterdam	13187.3	MOE	0.01	131.9	yes
24/09/2014	Churchill	Camden	Camden	2931	MOE	0.01	29.3	yes
23/10/2014	Churchill	Brunsbüttel	Brunsbüttel	8840	MOE	0.1	884	yes
26/10/2014	Churchill	Antwerp	Antwerp	15557	MOE	0.01	155.6	yes
01/10/2007	Deception Bay	Antwerp	Antwerp	0	No exchange	0.01	0	no
12/11/2007	Deception Bay	Aahrus	Aahrus	14946	MOE	0.1	1494.6	yes
01/10/2008	Deception Bay	Rotterdam	Eemshaven	0	No exchange	0.01	0	no
01/10/2008	Deception Bay	Antwerp	Eemshaven	0	No exchange	0.01	0	no
01/10/2008	Deception Bay	Eemshaven	Eemshaven	0	No exchange	0.1	0	no
24/07/2009	Deception Bay	Rotterdam	Eemshaven	54	MOE	0.01	0.5	yes
16/10/2009	Deception Bay	Rotterdam / Dunkirk	Eemshaven	0	MOE	0.01	0	no
09/09/2010	Deception Bay	Eemshaven	Eemshaven	0	MOE	0.1	0	no
17/09/2011	Deception Bay	Liverpool	Eemshaven	234	MOE	0.1	23.4	yes
21/10/2013	Deception Bay	Philadelphia	Philadelphia	4513	MOE	0.01	45.1	yes
09/12/2007	Iqaluit	Las Palmas / Shelburne	Sisimiut	0	No exchange	0.1	0	no
17/09/2009	Iqaluit	Falmouth	Qaqortoq	0	MOE	0.1	0	no
21/08/2010	Iqaluit	Skagen	Ventspils	0	MOE	0.1	0	no
20/07/2009	Pangnirtung	Everett	Everett	0	No exchange	0.1	0	no
22/08/2010	Pond Inlet	Hamburg	Uummannaq	0	No exchange	0.1	0	no
06/01/2009	Rankin Inlet	Antwerp	Rafnes	0	MOE	0.01	0	no
24/08/2008	Resolute Bay (Quassuittuq)	Copenhagen	Copenhagen	0	No exchange	0.1	0	no
12/08/2009	Tuktoyaktuk	San Francisco	San Francisco	0	MOE	0.1	0	no

Species: *Mya arenaria*

Pathway: Domestic vessels

Arrival Date	Arrival Port (Domestic)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
29/09/2007	Chesterfield	Sydney	Sydney	0	No exchange	1	0	no
07/10/2005	Churchill	Sept Iles	Sept Iles	11397	No exchange	1	11397	yes
18/08/2007	Churchill	Port Alfred	Port Alfred	16074	MOE	0.01	160.7	yes
29/09/2014	Churchill	Sept Iles	Sept Iles	16764.7	MOE	0.1	1676.5	yes
27/02/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
15/06/2005	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
22/08/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
01/10/2005	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
01/11/2005	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
30/12/2005	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
15/03/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
18/06/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
22/10/2006	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
27/11/2006	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
26/12/2006	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
04/02/2007	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
26/03/2007	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
27/08/2007	Deception Bay	Mulgrave	Mulgrave	0	Coastal	1	0	no
13/09/2007	Deception Bay	Lower Cove	Lower Cove	0	No exchange	1	0	no
23/09/2007	Deception Bay	Lower Cove	Lower Cove	0	No exchange	1	0	no
11/11/2007	Deception Bay	Saint John	Saint John	3653	MOE	0.1	365.3	yes
04/01/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
07/03/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
18/04/2008	Deception Bay	Chicoutimi	Chicoutimi	5712	Coastal	1	5712	yes
17/06/2008	Deception Bay	Becancour	Becancour	10253	Coastal	1	10253	yes
22/07/2008	Deception Bay	Montreal	Montreal	10253	Coastal	1	10253	yes
11/08/2008	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
28/08/2008	Deception Bay	Belledune	Belledune	5000	No exchange	1	5000	yes
15/09/2008	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
11/10/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
19/12/2008	Deception Bay	Chicoutimi	Chicoutimi	10253	Coastal	1	10253	yes
15/06/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/06/2013	Deception Bay	Montreal	Montreal	3419.1	Coastal	1	3419.1	yes

Arrival Date	Arrival Port (Domestic)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
20/07/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/08/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
02/09/2013	Deception Bay	Quebec	Quebec	7257	Coastal	1	7257	yes
02/10/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
14/10/2013	Deception Bay	Summerside	Summerside	5671	No exchange	1	5671	yes
18/10/2013	Deception Bay	Quebec	Quebec	4774	Coastal	1	4774	yes
03/11/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
05/12/2013	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
11/01/2014	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
28/02/2014	Deception Bay	Quebec	Quebec	10253	Coastal	1	10253	yes
22/07/2014	Deception Bay	Contrecoeur	Contrecoeur	7363	Coastal	1	7363	yes
23/08/2014	Deception Bay	Quebec	Quebec	9072	Coastal	1	9072	yes
18/09/2014	Deception Bay	Quebec	Quebec	8432	Coastal	1	8432	yes
16/10/2014	Deception Bay	Quebec	Quebec	7350	Coastal	1	7350	yes
21/08/2005	Kuujjuaraapik (Great Whale)	Montreal	Montreal	690	MOE	0.01	6.9	yes

Species: *Mya arenaria*

Pathway: International vessels

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
17/10/2010	Chesterfield	Rotterdam	Antwerp	0	MOE	0.01	0	no
11/08/2005	Churchill	Newport News	Newport News	2779	MOE	0.1	277.9	yes
03/09/2005	Churchill	Greenore	Greenore	9188	MOE	0.1	918.8	yes
11/09/2005	Churchill	Newport News	Newport News	6346	MOE	0.1	634.6	yes
15/09/2005	Churchill	Port Everglades	Port Everglades	9309	MOE	0.1	930.9	yes
18/09/2005	Churchill	Baltimore	Baltimore	10489	MOE	0.1	1048.9	yes
21/09/2005	Churchill	Ijmuiden	Ijmuiden	17656	MOE	0.1	1765.6	yes
28/09/2005	Churchill	Savannah	Savannah	958	MOE	0.1	95.8	yes
28/09/2005	Churchill	Tampa	Tampa	4236	MOE	0.01	42.4	yes
06/10/2005	Churchill	Baltimore	Baltimore	5505	MOE	0.1	550.5	yes
20/08/2006	Churchill	Charleston	Charleston	17114	MOE	0.1	1711.4	yes
04/09/2006	Churchill	Belfast	Belfast	4764	MOE	0.1	476.4	yes
04/09/2006	Churchill	Foynes	Belfast	6861	MOE	0.1	686.1	yes

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
04/09/2006	Churchill	Belfast	Belfast	931	MOE	0.1	93.1	yes
04/09/2006	Churchill	Foynes	Foynes	6852	MOE	0.1	685.2	yes
13/09/2006	Churchill	London	London	11515	MOE	0.01	115.2	yes
14/09/2006	Churchill	Aughinish	Aughinish	0	No exchange	0.1	0	no
27/09/2006	Churchill	Amsterdam	Amsterdam	32901	MOE	0.1	3290.1	yes
11/10/2006	Churchill	Terneuzen	Terneuzen	31358	MOE	0.1	3135.8	yes
13/10/2006	Churchill	Dublin	Falmouth	10087	MOE	0.1	1008.7	yes
15/10/2006	Churchill	Dublin	Dublin	10051	MOE	0.1	1005.1	yes
11/08/2007	Churchill	Hamburg	Hamburg	11397	MOE	0.1	1139.7	yes
22/08/2007	Churchill	Klaipeda	Klaipeda	13466	MOE	0.1	1346.6	yes
27/08/2007	Churchill	Ronnskar	Ronnskar	10680	MOE	0.1	1068	yes
27/08/2007	Churchill	Ronnskar	Skagen	11156	MOE	0.1	1115.6	yes
04/09/2007	Churchill	Antwerp	Antwerp	2696	MOE	0.01	27	yes
04/09/2007	Churchill	Newport	Antwerp	5615	MOE	0.01	56.2	yes
04/09/2007	Churchill	Antwerp	Antwerp	1348	MOE	0.01	13.5	yes
04/09/2007	Churchill	Newport	Newport	5615	MOE	0.01	56.2	yes
25/09/2007	Churchill	Sunndalsora	Sunndalsora	14451	MOE	0.1	1445.1	yes
02/10/2007	Churchill	Bremen	Bremen	10697	MOE	0.01	107	yes
05/10/2007	Churchill	Londonderry	Londonderry	14226	MOE	0.1	1422.6	yes
05/10/2007	Churchill	Liverpool	Londonderry	3228	MOE	0.1	322.8	yes
11/10/2007	Churchill	Dublin	Dublin	6818	MOE	0.1	681.8	yes
11/10/2007	Churchill	Portbury	Portbury	9629	MOE	0.1	962.9	yes
11/10/2007	Churchill	Dublin	Portbury	6818	MOE	0.1	681.8	yes
16/10/2007	Churchill	Tyne	Muuga-Port Of Tallinn	0	MOE	0.01	0	no
08/11/2007	Churchill	Hamburg	Unknown	11397	MOE	0.1	1139.7	yes
04/08/2008	Churchill	Szczecin	Szczecin	27426	MOE	0.1	2742.6	yes
08/08/2008	Churchill	Kaliningrad	Kaliningrad	0	MOE	0.1	0	no
13/08/2008	Churchill	Riga	Copenhagen	11627	MOE	0.1	1162.7	yes
13/08/2008	Churchill	Riga	Riga	11624	MOE	0.1	1162.4	yes
21/08/2008	Churchill	Gdynia	Gdynia	7825	MOE	0.1	782.5	yes
21/08/2008	Churchill	Rotterdam	Rotterdam	8398	MOE	0.01	84	yes
08/09/2008	Churchill	Teesport	Teesport	977	MOE	0.1	97.7	yes
08/09/2008	Churchill	Teesport	Teesport	9188	MOE	0.1	918.8	yes
14/09/2008	Churchill	Amsterdam	Amsterdam	11394	MOE	0.1	1139.4	yes
19/09/2008	Churchill	Ghent	Ghent	10905	MOE	0.01	109.1	yes
19/09/2008	Churchill	Ghent	Ghent	220	MOE	0.01	2.2	yes

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
22/09/2008	Churchill	Straumsvik	Straumsvik	11866	MOE	0.1	1186.6	yes
30/09/2008	Churchill	Liepaja	Liepaja	372	MOE	0.1	37.2	yes
04/10/2008	Churchill	Ravenna	Ravenna	11571	MOE	0.1	1157.1	yes
13/10/2008	Churchill	Porto Marghera	Gibraltar	8561	MOE	0.1	856.1	yes
23/10/2008	Churchill	Sunndalsora	Sunndalsora	11636	MOE	0.1	1163.6	yes
11/08/2009	Churchill	Liepaja	Liepaja	9208	MOE	0.1	920.8	yes
25/08/2009	Churchill	Brest	Portland	5990	MOE	0.1	599	yes
30/08/2009	Churchill	Straumsvik	Straumsvik	10239	MOE	0.1	1023.9	yes
30/08/2009	Churchill	Straumsvik	Straumsvik	1888	MOE	0.1	188.8	yes
12/09/2009	Churchill	Ronnskar	Ronnskar	5746	MOE	0.1	574.6	yes
12/09/2009	Churchill	Brunsbüttel	Ronnskar	4338	MOE	0.1	433.8	yes
09/10/2009	Churchill	Vlissingen	Vlissingen	13634	MOE	0.1	1363.4	yes
15/10/2009	Churchill	Rotterdam	Rotterdam	2780	MOE	0.01	27.8	yes
27/07/2010	Churchill	Bari	Gibraltar	6532	MOE	0.1	653.2	yes
03/08/2010	Churchill	Hamburg	Nuuk	0	MOE	0.1	0	no
05/08/2010	Churchill	Klaipeda	Klaipeda	10570	MOE	0.1	1057	yes
17/08/2010	Churchill	Straumsvik	Straumsvik	14844	MOE	0.1	1484.4	yes
17/08/2010	Churchill	Reydarfjordu r	Straumsvik	10858	MOE	0.1	1085.8	yes
24/08/2010	Churchill	Newport	Falmouth	9548	MOE	0.01	95.5	yes
24/08/2010	Churchill	Falmouth	Falmouth	880	MOE	0.1	88	yes
26/08/2010	Churchill	Ghent	Ghent	10451	MOE	0.01	104.5	yes
30/08/2010	Churchill	Vlissingen	Vlissingen	7500	MOE	0.1	750	yes
14/08/2013	Churchill	Sauda	Sauda	27462	MOE	0.1	2746.2	yes
22/09/2013	Churchill	Reydarfjordu r	Reydarfjordu r	16071.6	MOE	0.1	1607.2	yes
27/09/2013	Churchill	Straumsvik	Straumsvik	10708	MOE	0.1	1070.8	yes
30/09/2013	Churchill	Antwerp	Antwerp	16333.4	MOE	0.01	163.3	yes
06/10/2013	Churchill	Reydarfjordu r	Reydarfjordu r	13092	MOE	0.1	1309.2	yes
18/10/2013	Churchill	Ghent	Ghent	13759.5	MOE	0.01	137.6	yes
31/10/2013	Churchill	Karmoy	Karmoy	10285	MOE	0.1	1028.5	yes
03/11/2013	Churchill	Sauda	Sauda	2731.6	MOE	0.1	273.2	yes
09/08/2014	Churchill	Dunkirk	Dunkirk	14713.9	MOE	0.1	1471.4	yes
31/08/2014	Churchill	Tyne	Tyne	14358.6	MOE	0.01	143.6	yes
07/09/2014	Churchill	Ghent	Ghent	13277	MOE	0.01	132.8	yes
19/09/2014	Churchill	Rotterdam	Rotterdam	13187.3	MOE	0.01	131.9	yes
24/09/2014	Churchill	Camden	Camden	2931	MOE	0.01	29.3	yes

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
25/09/2014	Churchill	Straumsvik	Straumsvik	13482	MOE	0.1	1348.2	yes
23/10/2014	Churchill	Brunsbüttel	Brunsbüttel	8840	MOE	0.1	884	yes
26/10/2014	Churchill	Antwerp	Antwerp	15557	MOE	0.01	155.6	yes
14/08/2010	Clyde River	Reykjavik	Sisimiut	0	No exchange	0.1	0	no
01/10/2007	Deception Bay	Antwerp	Antwerp	0	No exchange	0.01	0	no
12/11/2007	Deception Bay	Aahrus	Aahrus	14946	MOE	0.1	1494.6	yes
01/10/2008	Deception Bay	Rotterdam	Eemshaven	0	No exchange	0.01	0	no
01/10/2008	Deception Bay	Antwerp	Eemshaven	0	No exchange	0.01	0	no
01/10/2008	Deception Bay	Eemshaven	Eemshaven	0	No exchange	0.1	0	no
24/07/2009	Deception Bay	Rotterdam	Eemshaven	54	MOE	0.01	0.5	yes
16/10/2009	Deception Bay	Rotterdam / Dunkirk	Eemshaven	0	MOE	0.01	0	no
09/09/2010	Deception Bay	Eemshaven	Eemshaven	0	MOE	0.1	0	no
17/09/2011	Deception Bay	Liverpool	Eemshaven	234	MOE	0.1	23.4	yes
21/10/2013	Deception Bay	Philadelphia	Philadelphia	4513	MOE	0.01	45.1	yes
09/12/2007	Iqaluit	Las Palmas / Shelburne	Sisimiut	0	No exchange	0.1	0	no
11/08/2008	Iqaluit	Reykjavik	Reykjavik	0	No exchange	0.1	0	no
10/09/2008	Iqaluit	Reykjavik	Reykjavik	0	No exchange	0.1	0	no
17/09/2009	Iqaluit	Falmouth	Qaqortoq	0	MOE	0.1	0	no
21/08/2010	Iqaluit	Skagen	Ventspils	0	MOE	0.1	0	no
17/09/2010	Iqaluit	Husavik	Narsaq	0	MOE	0.1	0	no
20/07/2009	Pangnirtung	Everett	Everett	0	No exchange	0.1	0	no
22/08/2010	Pond Inlet	Hamburg	Uummannaq	0	No exchange	0.1	0	no
06/01/2009	Rankin Inlet	Antwerp	Rafnes	0	MOE	0.01	0	no
24/08/2008	Resolute Bay (Quassuittuq)	Copenhagen	Copenhagen	0	No exchange	0.1	0	no
19/08/2008	Tuktoyaktuk	Ulsan	Ulsan	0	MOE	0.1	0	no
20/08/2008	Tuktoyaktuk	Hakodate	Hakodate	0	No exchange	0.1	0	no
24/09/2008	Tuktoyaktuk	Dutch Harbor	Dutch Harbor	0	No exchange	0.1	0	no
12/08/2009	Tuktoyaktuk	San Francisco	San Francisco	0	MOE	0.1	0	no

Species: *Paralithodes camtschaticus*

Pathway: International vessels

Arrival Date	Arrival Port (International)	Ballast water source	Source port	Total Volume / tank discharged per vessel (MT)	Exchange Type	Correction factor	corrected volume (MT)	BW discharged at port
24/09/2008	Tuktoyaktuk	Dutch Harbor	Dutch Harbor	0	No exchange	0.1	0	0

CONCLUSION GÉNÉRALE

The general objectives of the thesis were to characterize native and non-native benthic invertebrates in coastal regions of the Canadian Arctic and to evaluate the overall risk for future aquatic invasive species incursions with changes related to global warming and shipping activity. In the objectives section the *wheel of time* was presented, together with the questions that would be addressed within this thesis. Figure 21 shows the findings associated with those questions in each chapter.

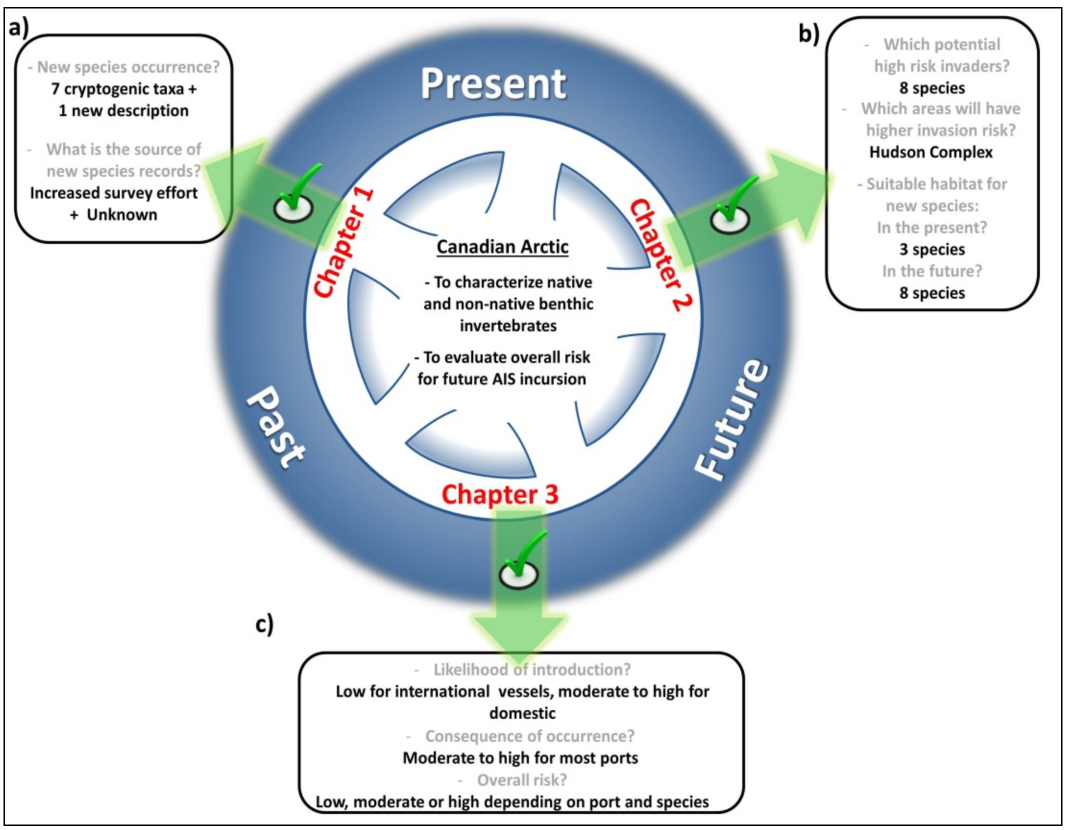


Figure 21: Conceptual model of thesis structure as a "*wheel of time*". It can be seen for each chapter which are the answers to the main questions that the thesis provided.

The general contributions of the ensemble of the thesis are described below, including the elaboration on specific findings provided by each chapter, together with a global view of the whole study.

STUDY CONTRIBUTIONS

Seven taxa were found to be cryptogenic in the Canadian Arctic

The surveys to establish baseline native species and NIS (Chapter 1) uncovered for the very first time in the Canadian Arctic five polychaetes species (*Aricidea* cf. *hartmani*, *Dipolydora socialis*, *Lumbrineris* cf. *zatsepini*, *Owenia borealis*, *Paraonides nordica*), one crustacean (*Onisimus sextoni* group) and one ascidian (*Heterostigma* sp.) (Section *a* in Figure 21). These new mentions were categorized as cryptogenic species (taxa that could be either native or non-native) (Carlton, 1996b). There is not enough evidence to consider these species as ship-mediated introductions. Nevertheless, it has to be remembered that the region might be much richer than observed in the survey, due to limitations of sampling effort. Species accumulation curves showed that the expected number of species exceeds the total number of observed species by 32%, meaning that more species remain to be identified. Still, the risk and the potential for receiving NIS in the region exist (as shown in Chapters 2 and 3). Furthermore, the discovery of living and viable non-indigenous barnacles on the hull of ships arriving to Canadian Arctic ports confirms a real potential for NIS arrival (Chan *et al.*, 2015). Continued sampling and monitoring in the region could contribute to the early detection of new introductions. The use of new molecular tools such as metabarcoding could help in such endeavors. Recently, genetic sequences of species that were not reported before in Canadian Arctic ports were found during CAISN research on water column samples (Brown *et al*. unpublished). This could indicate that these species are arriving in Canadian Arctic ports, but there may still be missing information on the establishment of populations and not enough effort to find individuals when sampling.

It is of the utmost importance that the information found in research is made available so others can use it and keep building knowledge from there. That is why the description of the cryptogenic species identified in Chapter 1 has been made available not only in the scientific literature, but also on the web. The list of cryptogenic species is publicly available in an information system on aquatic non-indigenous and cryptogenic species on the AquaNIS website (http://www.corpi.ku.lt/databases/index.php/aquanis/). This site stores and disseminates information on NIS introduction histories, recipient regions, taxonomy, biological traits, impacts, and other relevant documented data. It mainly contains data from European regions, and thanks to the results of this thesis, coverage has now been extended to the Canadian Arctic. Indeed, the cryptogenic species identified in Chapter 1 are the sole Canadian contributions to this database. Contributions like these are essential to start including data and information of the Canadian Arctic at a wider scale. This is non-trivial, since when searching literature on biodiversity and NIS it is remarkable that although there are many articles dealing with the Arctic in general, the Canadian Arctic is largely underrepresented. For instance the recent publications of Wassmann (2015) and Renaud *et al.* (2015) reference the entire Arctic Ocean, but the Canadian Arctic region is not well represented in the content. Contributions like the ones made in this thesis can help in highlighting the information available for the Canadian Arctic, both increasing the visibility of the region and pointing out the existing gaps in knowledge. Since from a policy perspective country borders are the accepted criterion for defining the origin of new species (Boonman-Berson & Turnhout, 2013), it is essential to identify the species that could be of concern for the Canadian territory.

Baseline study that contributed to increase the knowledge in native biodiversity of benthic invertebrates in the Canadian Arctic coasts

The distribution of benthic taxa along the Arctic coastline is poorly known, as is the extent of NIS incursions in the area. This lack of information may be explained by difficulties in surveying these regions. It is logistically complex and challenging to work in remote regions, particularly in benthic coastal areas of the Arctic. This has resulted in a low survey effort throughout the Arctic. Increasing survey effort for non-indigenous species gives the opportunity to improve our knowledge on the native biota as well. This thesis has made efforts to comprehensively sample benthic organisms in tidal and subtidal coastal Arctic habitats in order to improve baseline information, and provide a benchmark to allow the future tracking of potential changes in communities over time.

As a result of the findings in Chapter 1, there is now more available information on the biodiversity in coastal regions of the Canadian Arctic. A total of 236 species and genus were identified. More than three quarters of these species were known for the regions surveyed. However, between 7 to 15% of the species identified in Chapter 1 were described for the first time in new regions of the Canadian Arctic. Moreover, this baseline study contributed to the description of a new species of polychaete from the Family Cirratulidae: *Chaetozone careyi* (Blake, 2015) (Section *a* in Figure 21). This species was found on the coast of Deception Bay, and other individuals were found in Alaska and the Beaufort Sea by other researchers (Blake, 2015).

Another important contribution from Chapter 1 was the construction of a historical database containing information on benthic invertebrates described for the Canadian Arctic since 1932. This historical database is a compilation of the information on the presence, Arctic distribution and, when available, environmental information associated with species distributions. A total of 26 references with historical biodiversity information were assembled in one database. Having all this information compiled in one database will facilitate future international cooperation with other research groups, like the International Council for the Exploration of the Sea (ICES), to assemble a more extensive database that includes other taxonomic groups (e.g., phytoplankton and zooplankton). This is a major contribution at the international level that supports the collection of historical biodiversity information at a circumpolar scale.

Every species has its native range, making the invasion process a biogeographical process rather than taxonomic (Colautti & MacIsaac, 2004). This highlights the need to make reference to individual populations rather than entire species when talking about NIS. It is in this context that another significant contribution of this thesis is embedded: while constructing a baseline of native and non-native species in the Canadian Arctic, it was possible to find species that are native for the region studied, but that have been identified as NIS or cryptogenic somewhere else (Chapter 1). This makes the Canadian Arctic a potential source of NIS. This finding is in contrast to other studies that consider that the Canadian Arctic is unlikely to act as a source of NIS because the volume of ballast water leaving the region and dumped elsewhere is very low compared to other Canadian regions (Casas-Monroy *et al.*, 2014). Nevertheless, a ballast water vector with a low risk of species transport still represents a risk for invasion (Barry *et al.*, 2008). It thus cannot be taken for granted that the possibility of the Canadian Arctic acting as a source of NIS is non-existent. This is especially true for native Arctic species that are already known to be NIS or cryptogenic in ports that are connected to Canadian Arctic ports via shipping traffic (e.g., Atlantic coast of North America).

Lack of reliable data about the spatiotemporal occurrence of species has limited the ability of researchers to objectively assess the original distribution of species (Colautti & MacIsaac, 2004; Boonman-Berson & Turnhout, 2013). In addition, recognition of NIS requires knowledge of both taxonomic and biogeographic status of species, which is often unavailable (Ruiz *et al.*, 2015). Data from Chapter 1 provides information for future studies on biogeographic status of native species of the region. It also provides a benchmark for future monitoring and supports the development of methods for rapid detection of new species in the area, and provides information that could be used in future decision making.

The Canadian Arctic is already suitable for potential species introductions, ports in the Hudson Complex having the highest relative risk

A noteworthy contribution of this thesis is that the models of species distribution showed that under current environmental conditions the Canadian Arctic is already suitable for some AIS (Chapter 2, Section *b* in Figure 21). This reveals that the region is at risk since these species are present in ports that are connected to the Canadian Arctic via shipping (domestic and/or international) (Chapter 3, Section *c* in Figure 21). The potential range modelled for AIS through the environmental suitability models mean that the Canadian Arctic is already likely to provide the environmental conditions necessary for the survival and establishment of potential AIS. The species for which the habitat is suitable in the present (*Littorina littorea, Mya arenaria* and *Paralithodes camtschaticus*) are from the two major taxonomic groups known among documented NIS in North America: molluscs and crustaceans (Ruiz *et al.*, 2015). Once established, it is difficult to manage the spread of non-indigenous species. Studies like these ones are fundamental as an early warning signal and to identify the potential habitats and likely AIS (Chapters 2 and 3). In this way, vulnerable habitats can be identified prior to the establishment of potential invasive species, which can help focus the monitoring effort in these vulnerable habitats, as explained in Reiss *et al.* (2014).

Knowing that potential AIS are likely to survive and establish in the Arctic (Chapter 2), the next step was to enlarge the scope of the study using a combination of the relative likelihood of arrival on a vessel basis and the potential consequences of occurrence for each species (Chapter 3) in an attempt to assess ecological risk at the species specific level. This assessment showed that ports in the Canadian Arctic have a high likelihood of having already been exposed to the arrival of propagules of AIS that are established in connected ports. This situation is a major concern, given that the species assessed that have a history of invasion and impact elsewhere and that the regions where these propagules are arriving have moderate to high habitat sensitivity. Different criteria can be used for impact assessment, which makes the task difficult for the scientific community in measuring and evaluating impact (Boonman-Berson & Turnhout, 2013). The present study used known impact of species invasions in other environments to evaluate the consequence of occurrence in the Arctic. This study found that the main ports of Churchill and Deception Bay (Hudson Complex) have a higher relative risk of invasion compared to the other ports in the region for the likelihood of arrival, survival and establishment, and for the habitat sensitivity (Chapters 2 and 3, Section *b* in Figure 21). This is due to the fact that this region receives a higher proportion of vessels coming from locations where the species of concern are present, combined with the type of exchange performed, and because it is known that these ports have a higher environmental similarity with a large number of source ports (Chan *et al.*, 2012).

Knowing that the habitat is suitable for certain species, and that there are propagules that might be arriving in the region but have not yet been found in the environment brings the question of the possible mechanisms that could be contributing in the process:

- certain ecological barriers (reproductive, environmental and/or geographical) to species invasion may act as true barriers (Lockwood *et al.*, 2007),
- residents species could affect the survival of introduced species through interspecific interactions (Herborg *et al.*, 2007),
- more release events could be needed to increase the propagule number and, consequently, the likelihood of establishment (Locke *et al.*, 2007),
- transport may be successful, but the species might still lack the combination of adequate conditions for successful establishment. This has been called the "appearance of failure" hypothesis (Carlton, 1996a), and
- the species may not arrive in good conditions after transportation and/or the mortality in transit may be too high, resulting in an insufficient number of propagules for the resistance against inevitable stochastic shocks (Locke *et al.*, 2007).

Nevertheless, the findings of likelihood of introduction and consequence of occurrence provided by Chapters 2 and 3 present a comprehensive way to map potential habitat suitability and assess overall risk for NIS in the Canadian Arctic, and could help in developing an early warning system before invasions take place.

Domestic shipping can pose a higher relative risk than international shipping

Temporal and spatial differences were found when analyzing vessel-specific arrivals and their volumes of ballast water discharged (Chapter 3). In the last 10 years, Deception Bay was the port being exposed to a higher overall risk based on vessel specific annual averages when compared to Churchill and the other ports in the Canadian Arctic. This study highlights the importance of identifying and assessing the relative risks of the different pathways, which contribute to the identification of potential introductions.

Another important contribution of this thesis is that contrary to what is normally believed; the average likelihood per vessel arrival of domestic vessels to Canadian Arctic ports had a higher relative risk when compared to international vessels (Chapter 3, Section *c* in Figure 21). The most important result is that domestic ports would be contributing to a greater propagule pressure on a vessel basis. This can be explained given that most of the domestic vessels discharging ballast water in Canadian Arctic ports have previously exchanged ballast water in coastal areas. This highlights the importance of considering type of exchange when doing risk assessment and doing it at a species level. Risk will increase for these vessels when the species being assessed are potential AIS previously established in the coastal regions where the vessels complete their coastal exchange. In this sense, the results of this thesis highlight the fact that risk is expected to vary among ports as a function of the source, volume of ballast water discharge and treatment applied.

The amount of potential AIS and their suitable habitat will increase in the future in a global warming scenario

The results of this thesis not only demonstrate that the region of study has habitat that is suitable for potential AIS under current environmental conditions, but also that this suitability will continue to increase by mid-century in a global warming scenario (Chapter 2). The number of potential species for which the habitat would be appropriate for survival and establishment will also increase (Section *b* in Figure 21). The species distribution model showed that the habitat was appropriate not only for the three species with habitat suitability in the present (*L. littorea, M. arenaria* and *P. camtshcaticus*), but also for all the other species included in the modelling in the future: *Caprella mutica, Carcinus maenas, Amphibalanus improvisus, Membranipora membranacea* and *Botrylloides violaceus.* Predicting future changes is always associated with an inevitable degree of uncertainty (Wenger *et al.*, 2013). This is why these results should be interpreted as indications of possible future changes. Regardless of this level of uncertainty, species distribution models are known for being a useful tool to forecast the possible effects of climate change on benthic species distribution patterns and to support ecosystem management (Reiss *et al.*, 2014).

It is known that climatic change can, among other effects, lead to changes in the patterns of species' distribution and in biodiversity (Harley *et al.*, 2006). This brings a potential problem since biodiversity and ecosystem structure in the Arctic ecoregions are likely to be particularly sensitive to species shifts (Cheung *et al.*, 2011). The findings of this study provide valuable information that could help managers to evaluate where and how to monitor species of concern and vulnerable habitats. In addition, the results of Chapter 2 on projected habitat suitability in the present and under future conditions are unique, since the Canadian Arctic region has not been widely assessed for risks imposed by specific AIS.

Framework for NIS study in remote areas

One of the main contributions of the thesis as a whole is that the ensemble of the chapters can be considered as a framework to assess the state of NIS in remote regions where not enough information is available and where the potential to receive newly introduced species exists (Figure 22). As seen through the entire thesis, several characteristics of the Canadian Arctic contribute to the risk of new introductions:

- shipping can already act as a vector with the current level of activities in the region (domestic and international arrivals) (Chan *et al.*, 2012),
- ballast water is being discharged and fouled ships are arriving in the region (Chan *et al.*, 2012; Chan *et al.*, 2015),
- an increase in shipping is expected due to the increase in resource development projects (Gavrilchuk & Lesage, 2014), and

- global warming will likely increase shipping activity in the near future, therefore increasing the risk of introductions (Smith & Stephenson, 2013; Miller & Ruiz, 2014).

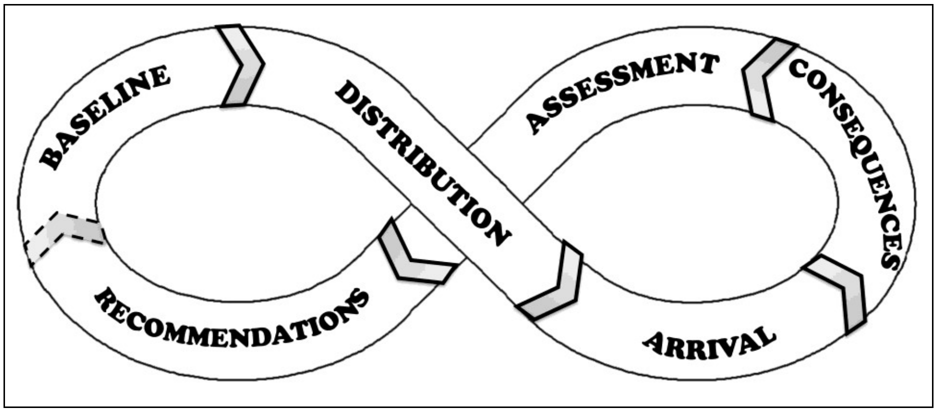


Figure 22: Framework for NIS studies in remote areas proposed from the present thesis.

In the context of the previously presented risk of new introductions' characteristics in the region, in addition with the general lack of information on the coastal biodiversity and on NIS, the steps for the implementation of the proposed framework are:

1. **Baseline:** the starting point is to do a baseline study (Chapter 1). This will help in setting the status of the region of interest in relation to NIS and find out whether there are NIS already established or not. This will also constitute a reference for comparisons in future studies. If any newly introduced species are found in the survey, the following steps of the framework can be done using these species. Otherwise, as shown in Chapter 2 and 3, species with the potential of arrival and known to be AIS in other regions can also be used.

2. **Distribution:** this step makes reference to two different approaches that should follow each other. The first is checking the known distributions and biogeography for all the species found during the baseline study (Chapter 1). This should be followed by modelling of the distribution for species of interest (either those

identified in the survey or by choosing potential AIS, as outlined in Chapter 2), which can be interpreted as the likelihood of survival and establishment.

3. **Arrival:** this step comprises gathering information on the number of arrivals, sources of ballast water and last port of call, ballast water treatment, volume of ballast water discharged and transit time in order to estimate de likelihood of arrival (Chapter 3).

4. **Consequences:** collect information on known impacts of the species in other environments and the habitat sensitivity of the region studied to make an estimation of the potential consequences of occurrence of AIS (Chapter 3).

5. **Assessment:** All elements mentioned above are then used to conduct an assessment to estimate overall risk considering the likelihood of introduction and the consequence of occurrence for the species and the region studied (Chapter 3).

6. **Recommendation:** Overall risk can provide the information needed for scientifically-based recommendations. Depending on the results obtained, the recommendation can vary from monitoring the region, to continued control of new introductions, or even recommendation of mitigation measures if necessary.

Given the evidence shown in the three Chapters of this thesis, with the application of the proposed framework for the Canadian Arctic, one of the recommendations that could be implemented is the maintenance of the surveying and monitoring programs for the detection of newly introduced species (with various techniques). This could in turn serve as a new baseline for future studies and risk assessments. It would also allow for continues evaluation and assessment of the region but a more complete baseline with a greater number of species.

FUTURE DIRECTIONS

The results of this thesis highlight the importance of the knowledge on diversity (for both native and NIS) while assessing the risks of potential introductions. Nevertheless, there are many aspects that remain to be studied and should be considered for future research.

Most of the work done in the present thesis, especially in the ecological risk assessment, considered mainly ballast water as a vector for the introduction of new species. However, another important vector is hull fouling. Hull fouling and ballast water are the dominant vectors for shipping related invasions in North American waters (Ruiz *et al.*, 2015). Contrary to ballast water, hull fouling is not being managed as a vector. Some management actions have been done with regards to hull fouling, but only to reduce drag and the associated increases in fuel consumption and travel time (Schultz *et al.*, 2011). Few studies have quantified the risk of introduction by hull fouling (Gollasch, 2002; Coutts & Taylor, 2004; Drake & Lodge, 2007; Chan *et al.*, 2015). In remote regions such as the Canadian Arctic, the studies of NIS and hull fouling are fewer still. The work of Chan *et al.* (2015) is an example of one of these studies. They found that the likelihood of a high risk introduction event is greater in hull fouling than in ballast water. Further studies on the probability of introduction with hull fouling as a vector should be a focus of future research.

An aspect planned for this thesis that was not achieved due to logistical constraints, was to study the settlement of species in the main ports of the Canadian Arctic using recruitment plates. Benthic invertebrates with larval development can be better understood when using recruitment plates, especially knowing that an established benthic population of species that can be transported by ballast water in their larval stage will rely on the colonization by larvae. Moreover, recruitment is a major factor determining the establishment, diversity and persistence of benthic species (Gaines & Bertness, 1992). However, a limited number of studies that evaluated recruitment in high latitude regions

(Schoener *et al.*, 1978; Pearse & Pearse, 1991; Barnes & Kukliński, 2005; Bowden, 2005) reported a slow colonization rate and the presence of colonists about an order of magnitude lower than described in most studies elsewhere in the world (Barnes & Kukliński, 2005). Further research on this would improve our knowledge on the establishment of NIS in high latitude regions given that recruitment and colonization information is essential to understand early community development.

While this thesis is one of a few studies predicting species distribution in Polar Regions, future research to complete and extend this work should include: the use of environmental variables at higher resolution, the use of other environmental variables that could not be included (e.g., type of sediment), an increase in the amount of species modelled, etc. Even though most of these factors are part of the limitations of the methodology, in the future it might be possible to have improved resolution of the variables. A particular focus should be paid to the inclusion of biotic factors in modelling exercises in future research. Increased research effort on fundamental ecology is required to consider the inclusion of biological factors for species distribution modelling considering that it is necessary to have *a priori* knowledge of species interactions and assume that they are constant in space and time (Wisz *et al.*, 2013; Reiss *et al.*, 2014). Nevertheless, it is a line of work worth exploring in Polar Regions (Wisz *et al.*, 2013). This offers better conditions for the development of modelling tools including biotic factors (Wisz *et al.*, 2013). Furthermore, the species distribution modelling methodology can be expanded to other assemblages than benthic communities, such as phytoplankton and zooplankton. Although a high proportion of aquatic invaders to date have been benthic (Streftaris *et al.*, 2005), these other assemblages have also been documented to pose an invasion risk due to ballast water discharge (Casas-Monroy *et al.*, 2015). Including these assemblages can contribute to a more complete understanding of the predicted distribution of potential introduced species.

A very interesting perspective to develop in the future would be the inclusion of spread in the ecological risk assessment. Spread is a component of the likelihood of introduction in the risk characterization together with arrival, survival and establishment of NIS, and includes the spreading of species through original or secondary pathways (Mandrak *et al.*, 2012). A high resolution model of oceanographic currents and an ice-ocean modelling system for nearshore coastal areas of the Arctic where ports are located is needed in order to include the spread of a species. There are oceanographic models that could be used, but their horizontal resolution varies from 10 to 18 km: a) the Canadian East Coast Ocean Model (CECOM), available for the Baffin Bay region and for the Gulf of St. Lawrence (Tang *et al.*, 2008), b) Nucleus for European Modelling of the Ocean (NEMO) available for the Arctic Ocean (Madec, 2008) and for the Hudson Complex model developed by Saucier *et al.* (2004). Nevertheless, the resolution needed to adequately include spread should be higher to decrease the possible error when modelling larval drift at the local scale of the port and surrounding regions (S. Senneville pers. comm.). Although the necessary information is currently not available at the resolution required for the use of high resolution model, spread should be a focus of future research.

Another work perspective for a more comprehensive ecological risk assessment is the inclusion of future scenarios with global warming and increased shipping activity. As seen throughout the thesis, the Canadian Arctic is expected to suffer from an increase in shipping traffic due to global warming changes (Smith & Stephenson, 2013; Miller & Ruiz, 2014). Different scenarios of expected ballast water discharge can be developed and used to compare with the current potential ecological risk. Not only could the increase in shipping and changes in climate be included in an ecological risk assessment for a future scenario, but changes in future ballast water treatments other than the exchange, such as the installation of UV systems on ships or chlorine treatments of ballast water, could also be considered. Since the year 2000, there has been an increasing interest in examining the efficacy of various treatment technologies, as reflected in the scientific literature (e.g., Bailey, 2015). The results of the different treatments can be used to generate alternative scenarios for their inclusion in ecological risk assessment studies. These will be important in early warning and identification of areas with higher ecological risk in the present and the future, helping in the planning of alternative management actions.

Finally, the framework developed for NIS studies in remote areas constitutes a major work perspective and one of the most important contributions of this thesis. The framework further identifies components that may improve the process of the assessment (some of them have been presented above):

- increase the sampling strategy in time and space,
- include biotic interactions in the modelling,
- include the sampling on the vectors for a more realistic estimation of propagules that are actually present in the ballast water of the ships discharging their waters in the ports of interest,
- include secondary spread,
- include hull fouling as a vector,
- perform laboratory experiments or even design experiments using benthocosms in order to measure potential impacts on local communities under similar environmental conditions to that of the region of interest, etc.

The framework is ideal for regions with scarce information. A potential place where the framework could be used is Greenland, one of the regions with high concentrations of Arctic fishing, domestic cargo and cruise ship traffic along its coast (Arctic-Council, 2009). Cruise ship traffic has been increasing so that the amount of passengers arriving each year is similar to half the population of Greenland (Arctic-Council, 2009). Even though these activities do not involve large amount of ballast water discharge, hull fouling could still be an important vector. On the other hand, Greenland has the potential to increase its resource exploitation due to their mineral deposits and this will require Arctic marine transport systems, increasing the potential amount of ballast water (Arctic-Council, 2009). Finally, there are few studies addressing the invasive species issue in the region (M. Sejr, pers. comm.). The proposed framework could be a tool for future research in similar regions.

CONCLUSION

The data gathered from the baseline study, the prediction of new species introductions and their related ecological risk constitute major contributions to the scientific knowledge base. They provide information for environmental management and decision making. This thesis establishes a point of reference for the Canadian Arctic region with regards to the introduction on new benthic species in the environment through time (i.e. past, present and future). It is expected that the thesis will contribute to future monitoring efforts and aid in the development of methods for the early detection of new species in the area. Lastly, a major contribution of the present study is that research on NIS provides an invaluable collateral result in understanding the biology, ecosystem functioning and general ecology of this poorly known region.

RÉFÉRENCES BIBLIOGRAPHIQUES

Aarluk-Consulting, and, G.L.L. & C, A. (2005) Strategic plan for the Iqaluit deepwater port project. http://www.city.iqaluit.nu.ca

Aitken, A. & Gilbert, R. (1986) The biota of intertidal flats at Pangnirtung Fiord, Baffin Island, Northwest Territories. Naturaliste canadien, 113(2), 191-200.

Aitken, A.E., Risk, M.J. & Howard, J.D. (1988) Animal-sediment relationships on a subarctic intertidal flat, Pangnirtung Fiord, Baffin Island, Canada. Journal of Sedimentary Research, 58(6)

Alvsvåg, J., Agnalt, A.L. & Jørstad, K.E. (2009) Evidence for a permanent establishment of the snow crab (*Chionoecetes opilio*) in the Barents Sea. Biological invasions, 11(3), 587-595.

Anisimova, N., Berenboim, B., Gerasimova, O., Manushin, I. & Pinchukov, M. (2005) On the effect of red king crab on some components of the Barents Sea ecosystem. Report PINRO, Murmansk

Appeltans, W., Ahyong, S.T., Anderson, G., Angel, M.V., Artois, T., Bailly, N., Bamber, R., Barber, A., Bartsch, I. & Berta, A. (2012a) The magnitude of global marine species diversity. Current Biology, 22, 2189-2202.

Appeltans, W., Bouchet, P., Boxshall, G.A., Fauchald, K., Gordon, D.P., Hoeksema, B.W., Poore, G.C.B., Van Soest, R.W.M., Stöhr, S. & Walter, T.C. (2012b) World register of marine species. Proceedings of the future of the 21st century ocean: Marine Sciences and European Research Infrastructures, Brest, France, 28, 30.

Appy, T.D., Linkletter, L.E. & Dadswell, M.J. (1980) A guide to the marine flora and fauna of the Bay of Fundy - Annelida Polychaeta. Ministère des approvisionnements et services, Ottawa, 124.

Archambault, P., Snelgrove, P.V.R., Fisher, J.A.D., Gagnon, J.M., Garbary, D.J., Harvey, M., Kenchington, E.L., Lesage, V., Levesque, M., Lovejoy, C., Mackas, D.L., McKindsey, C.W., Nelson, J.R., Pepin, P., Piché, L. & Poulin, M. (2010) From sea to sea: Canada's three oceans of biodiversity. PLoS ONE, 5(8): e12182. doi:10.1371/journal.pone.0012182

Arctic-Council (2009) Arctic Marine Shipping Assessment 2009.

Ashton, G.V., Willis, K.J., Burrows, M.T. & Cook, E.J. (2007) Environmental tolerance of *Caprella mutica*: Implications for its distribution as a marine non-native species. Marine Environmental Research, 64(3), 305-312.

Ashton, G.V., Riedlecker, E.I. & Ruiz, G.M. (2008a) First non-native crustacean established in coastal waters of Alaska. Aquatic Biology, 3(2), 133-137.

Ashton, G.V., Stevens, M.I., Hart, M.C., Green, D.H., Burrows, M.T., Cook, E.J. & Willis, K.J. (2008b) Mitochondrial DNA reveals multiple Northern Hemisphere introductions of *Caprella mutica* (Crustacea, Amphipoda). Molecular Ecology, 17(5), 1293-1303.

Atkinson, E.G. & Wacasey, J.W. (1989a) Benthic invertebrates collected from Hudson Strait, Foxe Channel and Foxe Basin, Canada, 1949 to 1970. Arctic Biological Station of the Institut Maurice-Lamontagne, Department of Fisheries and Oceans.

Atkinson, E.G. & Wacasey, J.W. (1989b) Benthic invertebrates collected from the western Canadian Arctic, 1951 to 1985. Arctic Biological Station of the Institut Maurice-Lamontagne, Department of Fisheries and Oceans.

Atkinson, E.G. & Wacasey, J.W. (1989c) Benthic invertebrates collected from Hudson Bay, Canada, 1953 to 1965. Canadian Data Report of Fisheries and Aquatic Sciences.

Bailey, S.A. (2015) An overview of thirty years of research on ballast water as a vector for aquatic invasive species to freshwater and marine environments. Aquatic Ecosystem Health & Management, (accepted).

Bailey, S.A., Deneau, M.G., Jean, L., Wiley, C.J., Leung, B. & MacIsaac, H.J. (2011) Evaluating efficacy of an environmental policy to prevent biological invasions. Environmental Science & Technology, 45(7), 2554-2561.

Baker, R.F. (1989) An environmental assessment and biological investigation of the Nelson River estuary. North/South Consultants.

Baker, R.F., Lawrence, M. & Schneider-Vieira, F. (1994) Physical and Chemical Oceanography and Aquatic Biota of the Churchill River estuary. August, 1993. North/South Consultants Inc., Winnipeg,

Barber, D.G., Galley, R., Asplin, M.G., De Abreu, R., Warner, K.A., Pućko, M., Gupta, M., Prinsenberg, S. & Julien, S. (2009) Perennial pack ice in the southern Beaufort Sea was not as it appeared in the summer of 2009. Geophysical Research Letters, 36 (24)

Barber, D.G., Ehn, J.K., Pućko, M., Rysgaard, S., Deming, J.W., Bowman, J.S., Papakyriakou, T., Galley, R.J. & Søgaard, D.H. (2014) Frost flowers on young Arctic sea ice: The climatic, chemical, and microbial significance of an emerging ice type. Journal of Geophysical Research: Atmospheres, 119(20), 11-593.

Barnes, D.K.A. & Kukliński, P. (2005) Low colonisation on artificial substrata in arctic Spitsbergen. Polar Biology, 29(1), 65-69.

Barnes, D.K.A., Hodgson, D.A., Convey, P., Allen, C.S. & Clarke, A. (2006) Incursion and excursion of Antarctic biota: past, present and future. Global Ecology and Biogeography, 15(2), 121-142.

Barry, S.C., Hayes, K.R., Hewitt, C.L., Behrens, H.L., Dragsund, E. & Bakke, S.M. (2008) Ballast water risk assessment: principles, processes, and methods. ICES Journal of Marine Science: Journal du Conseil, 65(2), 121-131.

Bax, N., Carlton, J.T., Mathews-Amos, A., Haedrich, R.L., Howarth, F.G., Purcell, J.E., Rieser, A. & Gray, A. (2001) The control of biological invasions in the world's oceans. Conservation Biology, 15(5), 1234-1246.

Beaugrand, G., Edwards, M. & Legendre, L. (2010) Marine biodiversity, ecosystem functioning, and carbon cycles. Proceedings of the National Academy of Sciences, 107(2), 10120-10124.

Berkeley, E. & Berkeley, C. (1943) Biological and Oceanographical Conditions in Hudson Bay: 11. Polychaeta from Hudson Bay. Journal of the Fisheries Board of Canada, 6(2), 129-132.

Berman, J., Harris, L., Lambert, W., Buttrick, M. & Dufresne, M. (1992) Recent invasions of the Gulf of Maine: three contrasting ecological histories. Conservation Biology, 6(3), 435-441.

Bernard, F.R. (1979) Bivalve mollusks of the western Beaufort Sea. Natural History Museum of Los Angeles County.

Bertness, M.D. (1984) Habitat and community modification by an introduced herbivorous snail. Ecology, 370-381.

Blake, J.A. (1991) Revision of some genera and species of Cirratulidae (Polychaeta) from the western North Atlantic. Ophelia supplement, 5, 17-30.

Blake, J.A. (2015) New species of Chaetozone and Tharyx (Polychaeta: Cirratulidae) from the Alaskan and Canadian Arctic and the Northeastern Pacific, including a description of the lectotype of *Chaetozone setosa* Malmgren from Spitsbergen in the Norwegian Arctic. Zootaxa, 3919(3), 501-552.

Blake, J.A. & Dean, D. (1973) Polychaetous Annelids Collected by the RV Hero from Baffin Island, Davis Straight, and West Greenland in 1968. Bulletin of the Southern California Academy of Sciences, 72(1), 31-39.

Bogich, T.L., Liebhold, A.M. & Shea, K. (2008) To sample or eradicate? A cost minimization model for monitoring and managing an invasive species. Journal of Applied Ecology, 45(4), 1134-1142.

Bomford, M. (2008) Risk assessment models for establishment of exotic vertebrates in Australia and New Zealand. Invasive Animals Cooperative Research Centre Canberra,, Australia.

Boonman-Berson, S. & Turnhout, E. (2013) Globalising biodiversity: scientific practices of scaling and databasing. Forest and Nature Governance, pp. 171-191. Springer.

Boos, K., Ashton, G.V. & Cook, E.J. (2011) The Japanese skeleton shrimp *Caprella mutica* (Crustacea, Amphipoda): a global invader of coastal waters. In the Wrong Place-Alien Marine Crustaceans: Distribution, Biology and Impacts, pp. 129-156. Springer.

Bouma, T.J., Olenin, S., Reise, K. & Ysebaert, T. (2009) Ecosystem engineering and biodiversity in coastal sediments: posing hypotheses. Helgoland Marine Research, 63(1), 95-106.

Bousfield, E.L. (1955) Ecological control of the occurrence of barnacles in the Miramichi estuary. Dept. of Northern Affairs and National Resources, National Parks Branch.

Bowden, D.A. (2005) Seasonality of recruitment in Antarctic sessile marine benthos. Marine Ecology Progress Series, 297, 101-118.

Boyd, M.J., Mulligan, T.J. & Shaughnessy, F.J. (2002) Non-indigenous marine species of Humboldt Bay, California.

Boyer, T. & Mishonov, A. (2013) World Ocean Atlas 2013 Product Documentation. In: Ocean Climate Laboratory, NODC/NESDIS/NOAA, Silver Spring, MD. , p. 14

Brawley, S.H., Coyer, J.A., Blakeslee, A.M.H., Hoarau, G., Johnson, L.E., Byers, J.E., Stam, W.T. & Olsen, J.L. (2009) Historical invasions of the intertidal zone of Atlantic North America associated with distinctive patterns of trade and emigration. Proceedings of the National Academy of Sciences, 106(2), 8239-8244.

Brenchley, G.A. & Carlton, J.T. (1983) Competitive displacement of native mud snails by introduced periwinkles in the New England intertidal zone. The Biological Bulletin, 165(3), 543-558.

Briski, E., Ghabooli, S., Bailey, S.A. & MacIsaac, H.J. (2012) Invasion risk posed by macroinvertebrates transported in ships' ballast tanks. Biological Invasions, 14(9), 1843-1850.

Britayev, T.A., Rzhavsky, A.V., Pavlova, L.V. & Dvoretskij, A.G. (2010) Studies on impact of the alien Red King Crab (*Paralithodes camtschaticus*) on the shallow water benthic communities of the Barents Sea. Journal of Applied Ichthyology, 26(s2), 66-73.

Broekhuysen, G.J. (1936) On development, growth and distribution of *Carcinides maenas* (L.). Archives Neerlandaises de Zoologie, 2(1), 257-400.

Brown, J.L. (2014) SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. Methods in Ecology and Evolution, 5(7), 694-700.

Burgiel, S., Foote, G., Orellana, M. & Perrault, A. (2006) Invasive alien species and trade: integrating prevention measures and international trade rules. The Center for International Environmental Law and Defenders of Wildlife, Washington, DC, 66-74.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M. & Halpern, B.S. (2011) The pace of shifting climate in marine and terrestrial ecosystems. Science, 334(6056), 652-655.

Buschbaum, C. & Gutow, L. (2005) Mass occurrence of an introduced crustacean (*Caprella cf. mutica*) in the south-eastern North Sea. Helgoland marine research, 59(3), 252-253.

Byers, J.E. (2005) Marine reserves enhance abundance but not competitive impacts of a harvested nonindigenous species. Ecology, 86(2), 487-500.

CAFF (2013) Arctic biodiversity assessment: status and trends in Arctic biodiversity. In: (ed. H. Meltofte), p. 556. Conservation of Arctic Flora and Fauna, Akureyri.

Capinha, C. & Anastácio, P. (2011) Assessing the environmental requirements of invaders using ensembles of distribution models. Diversity and Distributions, 17(1), 13-24.

Carlton, J.T. (1979) History, biogeography, and ecology of the introduced marine and estuarine invertebrates of the Pacific Coast of North America. (Doctoral dissertation, University of California, Davis).

Carlton, J.T. (1985) Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceanography and Marine Biology, 23, 313-371.

Carlton, J.T. (1992) Introduced marine and estuarine mollusks of North America: an end-of-the-20th-century perspective. Journal of Shellfish Research, 11(2), 489-505.

Carlton, J.T. (1996a) Pattern, process, and prediction in marine invasion ecology. Biological conservation, 78(1), 97-106.

Carlton, J.T. (1996b) Biological invasions and cryptogenic species. Ecology, 1653-1655.

Carlton, J.T. (1999) Molluscan invasions in marine and estuarine communities. Malacologia, 41(2), 439-454.

Carlton, J.T. (2001) Introduced species in US coastal waters.

Carlton, J.T. (2009) Deep invasion ecology and the assembly of communities in historical time. Biological invasions in marine ecosystems, pp. 13-56. Springer.

Carlton, J.T. (2011) The Inviolate Sea? Charles Elton and Biological Invasions in the World's Oceans. Fifty Years of Inavasion Ecology, 25p.

Carlton, J.T. & Geller, J.B. (1991) Ecological roulette: the global transport of nonindigenous marine organisms. Chemical Physics Letter, 179, 53.

Carlton, J.T. & Cohen, A.N. (2003) Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. Journal of Biogeography, 30(12), 1809-1820.

Carlton, J.T., Newman, W.A. & Pitombo, F.B. (2011) Barnacle invasions: introduced, cryptogenic, and range expanding Cirripedia of North and South America. In the Wrong Place-Alien Marine Crustaceans: Distribution, Biology and Impacts, pp. 159-213. Springer.

Carmack, E. & McLaughlin, F. (2011) Towards recognition of physical and geochemical change in Subarctic and Arctic Seas. Progress in Oceanography, 90(1), 90-104.

Carr, C.M. (2012) Polychaete diversity and distribution patterns in Canadian marine waters. Marine Biodiversity, 42(2), 93-107.

Carver, C.E. & Mallet, A.L. (2002) An assessment of the risk of ballast water-mediated introduction of non-indigenous phytoplankton and zooplankton into Atlantic Canadian waters. Dartmouth, NS: Transport Canada,

Casas-Monroy, O., Roy, S. & Rochon, A. (2011) Ballast sediment-mediated transport of non-indigenous species of dinoflagellates on the East Coast of Canada. Aquatic Invasion, 6, 231-248.

Casas-Monroy, O., Linley, R.D., Adams, J.K., Chan, F.T., Drake, D.A.R. & Bailey, S.A. (2014) National Risk Assessment for Introduction of Aquatic Nonindigenous

Species to Canada by Ballast Water. In, p. vi + 73 p. Canadian science Advisory Secretariat (CSAS)

Casas-Monroy, O., Linley, R.D., Adams, J.K., Chan, F.T., Drake, D.A.R. & Bailey, S.A. (2015) Relative Invasion Risk for Plankton across Marine and Freshwater Systems: Examining Efficacy of Proposed International Ballast Water Discharge Standards. PloS one, 10(3), e0118267.

Castillo, J.G. (1976) Analysis of the benthic Cumacea and Gammaridean Amphipoda from the western Beaufort Sea. (Doctoral dissertation, Oregon State University).

Chan, F., Bailey, S., Wiley, C. & MacIsaac, H. (2013) Relative risk assessment for ballast-mediated invasions at Canadian Arctic ports. Biological Invasions, 15(2), 295-308.

Chan, F.T., MacIsaac, H.J. & Bailey, S.A. (2015) Relative importance of vessel hull fouling and ballast water as transport vectors of nonindigenous species to the Canadian Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 72(8): 1230-1242.

Chan, F.T., Bronnenhuber, J.E., Bradie, J.N., Howland, K.L., Simard, N. & Bailey, S.A. (2012) Risk Assessment for ship-mediated introductions of aquatic nonindigenous species to the Canadian Arctic. In, p. 93. Fisheries and Oceans Canada, Canada.

Chang, A.L., Blakeslee, A.M.H., Miller, A.W. & Ruiz, G.M. (2011) Establishment failure in biological invasions: a case history of *Littorina littorea* in California, USA. PloS one, 6, e16035.

Chao, A. (1984) Nonparametric estimation of the number of classes in a population. Scandinavian Journal of statistics, 265-270.

Chapman, J.W., Carlton, J.T., Bellinger, M.R. & Blakeslee, A.M.H. (2007) Premature refutation of a human-mediated marine species introduction: the case history of the marine snail *Littorina littorea* in the Northwestern Atlantic. Biological Invasions, 9(8), 995-1008.

Chase, M.E. & Thomas, M.L.H. (1995) The effect of the rate and onset of temperature increase on spawning of the periwinkle, *Littorina littorea* (L.). Journal of Experimental Marine Biology and Ecology, 186(2), 277-287.

Cheung, W.W.L., Zeller, D. & Pauly, D. (2011) Projected species shifts due to climate change in the Canadian marine ecoregions. A report prepared for Environment Canada.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R. & Pauly, D. (2009) Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 10(3), 235-251.

Chust, G., Castellani, C., Licandro, P., Ibaibarriaga, L., Sagarminaga, Y. & Irigoien, X. (2013) Are *Calanus* spp. shifting poleward in the North Atlantic? A habitat modelling approach. ICES Journal of Marine Science: Journal du Conseil, fst147.

Çinar, M.E. (2013) Alien polychaete species worldwide: current status and their impacts. Journal of the Marine Biological Association of the United Kingdom, 93(05), 1257-1278.

Clarke, K.R. & Gorley, R.N. (2006) PRIMER v6: Manual/Tutorial. PRIMER-E, Plymouth,

Cockrell, M.L. & Sorte, C.J.B. (2013) Predicting climate-induced changes in population dynamics of invasive species in a marine epibenthic community. Journal of Experimental Marine Biology and Ecology, 440, 42-48.

Cohen, A.N. & Carlton, J.T. (1998) Accelerating invasion rate in a highly invaded estuary. Science, 5350(29), 555-558.

Colautti, R.I. & MacIsaac, H.J. (2004) A neutral terminology to define 'invasive'species. Diversity and Distributions, 10(2), 135-141.

Colautti, R.I., Grigorovich, I.A. & MacIsaac, H.J. (2006a) Propagule pressure: a null model for biological invasions. Biological Invasions, 8(5), 1023-1037.

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

Colwell, R.K. & Coddington, J.A. (1994) Estimating terrestrial biodiversity through extrapolation. Philosophical Transactions of the Royal Society B: Biological Sciences, 345, 101-118.

Compton, T.J., Leathwick, J.R. & Inglis, G.J. (2010) Thermogeography predicts the potential global range of the invasive European green crab (*Carcinus maenas*). Diversity and Distributions, 16(2), 243-255.

Conover & Stewart (1978) Marine benthic invertebrates of the Southern Davis Strait and Ungava Bay. Arctic petroleum operators association projects, Report for Imperial Oil Ltd, Aquitaine Co. Of Canada Ltd. And Canada cities services Ltd.

Cook, E.J., Jahnke, M., Kerckhof, F., Minchin, D., Faasse, M., Boos, K. & Ashton, G. (2007) European expansion of the introduced amphipod *Caprella mutica* Schurin 1935. Aquatic Invasions, 2(4), 411-421.

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

Coutts, A.D.M. & Taylor, M.D. (2004) A preliminary investigation of biosecurity risks associated with biofouling on merchant vessels in New Zealand. New Zealand Journal of Marine and Freshwater Research, 38(2), 215-229.

Coutts, A.D.M. & Dodgshun, T.J. (2007) The nature and extent of organisms in vessel sea-chests: a protected mechanism for marine bioinvasions. Marine Pollution Bulletin, 54(7), 875-886.

Crafton, R.E. (2014) Modeling invasion risk for coastal marine species utilizing environmental and transport vector data. Hydrobiologia, 746(1), 349-362.

Crocetta, F. & Turolla, E. (2011) *Mya arenaria* Linné, 1758 (Mollusca: Bivalvia) in the Mediterranean Sea: its distribution revisited. Journal of Biological Research-Thessaloniki, 16, 188-193.

Curtis, M.A. (1972) Depth distributions of benthic polychaetes in two fiords on Ellesmere Island, NWT. Journal of the Fisheries Board of Canada, 29(9), 1319-1327.

Cusson, M., Archambault, P. & Aitken, A. (2007) Biodiversity of benthic assemblages on the Arctic continental shelf: historical data from Canada. Marine ecology progress series, 331, 291-304.

Dahle, S., Denisenko, S.G., Denisenko, N.V. & Cochrane, S.J. (1998) Benthic fauna in the Pechora Sea. Sarsia, 83(3), 183-210.

David, M., Gollasch, S., Leppäkoski, E. & Hewitt, C. (2015) Risk assessment in ballast water management. Global Maritime Transport and Ballast Water Management, pp. 133-169. Springer.

Dawson, M. (2002) Plant quarantine: a tool for preventing the introduction and spread of alien species harmful to plants. Alien Invaders in Canada's Waters, Wetlands and Forests. Edited by R. Claudi, P. Nantel, and E. Muckle-Jeffs. Canadian Forest Service, Ottawa, Ont, 243-251.

de Rivera, C.E., Steves, B.P., Fofonoff, P.W., Hines, A.H. & Ruiz, G.M. (2011) Potential for high-latitude marine invasions along western North America. Diversity and Distributions, 17(6), 1198-1209.

DiBacco, C., Humphrey, D.B., Nasmith, L.E. & Levings, C.D. (2012) Ballast water transport of non-indigenous zooplankton to Canadian ports. ICES Journal of Marine Science: Journal du Conseil, 69(3), 483-491.

Dineen Jr, J.F. & Hines, A.H. (1992) Interactive effects of salinity and adult extract upon settlement of the estuarine barnacle *Balanus improvisus* (Darwin, 1854). Journal of experimental marine biology and ecology, 156(2), 239-252.

Doney, S.C., Ruckelshaus, M., Emmett Duffy, J., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J. & Talley, L.D. (2012) Climate Change Impacts on Marine Ecosystems. Annual Review of Marine Science, 4, 11-37.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B. & Leitão, P.J. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography, 36(1), 027-046.

Drake, J.M. & Lodge, D.M. (2007) Hull fouling is a risk factor for intercontinental species exchange in aquatic ecosystems. Aquatic Invasions, 2(2), 121-131.

Drake, J.M., Lodge, D.M. & Lewis, M. (2005) Theory and preliminary analysis of species invasions from ballast water: controlling discharge volume and location. The American midland naturalist, 154(2), 459-470.

Dvoretsky, A.G. & Dvoretsky, V.G. (2009) Fouling community of the red king crab, *Paralithodes camtschaticus* (Tilesius 1815), in a subarctic fjord of the Barents Sea. Polar biology, 32(7), 1047-1054.

Eastwood, M.M., Donahue, M.J. & Fowler, A.E. (2007) Reconstructing past biological invasions: niche shifts in response to invasive predators and competitors. Biological Invasions, 9(4), 397-407.

Elith, J. & Leathwick, J.R. (2009) Species distribution models: ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics, 40(1), 677.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E. & Yates, C.J. (2011) A statistical explanation of MaxEnt for ecologists. Diversity and Distributions, 17(1), 43-57.

Elith, J., Graham, C.H., Anderson, R.P., Dudı´k, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J.M., Peterson, A.T., Phillips, S.J., Richardson, K.S., Scachetti-Pereira, R., Schapire, R.E., Sobero´n, J., Williams, S., Wisz, M.S. & Zimmermann, N.E. (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography, 29(2), 129-151.

Ellis, D.V. (1957) Marine Infaunal Benthos in Arctic North America-select quantitative survey tables.

Ellis, D.V. (1960) Marine infaunal benthos in arctic North America. Arctic Institute of North America.

Ellis, D.V. & Wilce, R.T. (1961) Arctic and subarctic examples of intertidal zonation. Arctic, 224-235.

Elrich, P.R., Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.J., Rejmánek, M. & Williamson, M. (1989) Attributes of invaders and the invading process: Vertebrates. Biological invasions: a global perspective. Wiley, Chichester, UK, 315-327.

Elton, C.S. (1958) The ecology of invasions by plants and animals. Methuen, London, vol 18, Methuen and Co. Ltd.

Englund, V.P.M. & Heino, M.P. (1994) *In situ* measurement of seasonal variation in burial depth of *Mya arenaria* Linné. Journal of Molluscan Studies, 60(4), 465-467.

Environment_Natural_Resources (2015) Trends in shipping in the Northwest Passage and the Beaufort Sea. Available at: http://www.enr.gov.nt.ca/state-environment/73-trends-shipping-northwest-passage-and-beaufort-sea (accessed August 31st 2015).

Epelbaum, A., Herborg, L.M., Therriault, T.W. & Pearce, C.M. (2009) Temperature and salinity effects on growth, survival, reproduction, and potential distribution of two non-indigenous botryllid ascidians in British Columbia. Journal of Experimental Marine Biology and Ecology, 369(1), 43-52.

Falk-Petersen, J., Renaud, P. & Anisimova, N. (2011) Establishment and ecosystem effects of the alien invasive red king crab (*Paralithodes camtschaticus*) in the Barents Sea–a review. ICES Journal of Marine Science: Journal du Conseil, 68(3), 479-488.

Fetterer, F., Knowles, K., Meier, W. & Savoie, M. (2002) updated 2010: Sea ice index. National Snow and Ice Data Center, digital media. Available online at http://nsidc.org/data/seaice_index/archives/

Floerl, O. (2014) Management challenges and opportunities for marine biosecurity in the Arctic. Marine invasive species in the Arctic (ed. by L. Fernandez, B. Kaiser, N. Vestergaard, G.G. Þórarinsdóttir, K. Gunnarsson and Ó.S. Gíslason), p. 199. Norræna ráðherranefndin, Copenhagen.

Force, U.S.A.N.S.T. (1996) Report to the aquatic nuisance species task force. Generic nonindigenous aquatic organisms risk analysis review process (For Estimating Risk Associated with the Introduction of Nonindigenous Aquatic Organisms and how to Manage for that Risk). US Fish & Wildlife Service and National Oceanic & Atmospheric Administration. Risk Assessment and Management Committee.

Fretter, V. & Graham, A. (1985) The prosobranch molluscs of Britain and Denmark: Part 8-Neogastropoda.

Frey, M.A., Gartner, H.N., Murray, C.C. & Therriault, T.W. (2009) First confirmed records of the non-native amphipod *Caprella mutica* (Schurin 1935) along the coast of British Columbia, Canada, and the potential for secondary spread via hull fouling. Aquatic Invasions, 4(3), 495-499.

Frey, M.A., Simard, N., Robichaud, D.D., Martin, J.L. & Therriault, T.W. (2014) Fouling around: vessel sea-chests as a vector for the introduction and spread of aquatic invasive species. Management of Biological Invasions, 5(1), 21-30.

Furman, E.R. & Yule, A.B. (1991) *Balanus improvisus* Darwin in British estuaries: gene-flow and recolonisation, In Estuaries and Coasts: Spatial and Temporal Intercomparisons: ECSA19 Symposium, 4-8 September 1989, University of Caen, France (pp. 273-276). Olsen and Olsen, Denmark.

Gaines, S.D. & Bertness, M.D. (1992) Dispersal of juveniles and variable recruitment in sessile marine species. Nature, 360, 579-580.

García-de-Lomas, J. & Vilà, M. (2015) Lists of harmful alien organisms: Are the national regulations adapted to the global world? Biological Invasions, 17(11), 3081-3091.

García-Roselló, E., Guisande, C., Manjarrés-Hernández, A., González-Dacosta, J., Heine, J., Pelayo-Villamil, P., González-Vilas, L., Vari, R.P., Vaamonde, A., Granado-Lorencio, C. & Lobo, J.M. (2015) Can we derive macroecological patterns from primary Global Biodiversity Information Facility data? Global Ecology and Biogeography, 24(3), 335-347.

Gavrilchuk, K. & Lesage, V. (2014) Large-scale marine development projects (mineral, oil and gas, infrastructure) proposed for Canada's North. In, p. viii + 84pp. Canadian Technical Report of Fisheries and Aquatic Sciences

GBIF (2013) Global Biodiversity Information Facility. Available at: http://data.gbif.org (accessed June-August 2013).

Geller, J.B. (1996) Molecular approaches to the study of marine biological invasions. In: Molecular Zoology Advances, Strategies, andProtocols (eds Ferraris, J.D. & Palumbi, S.R.). Wiley, New York,pp. 119–132.

Gendron, L., Tamigneaux, E., Leroux, C. & Leblanc, M.-J. (2010) Adjustments to the schedule of kelp culture has long stipe (*Saccharina longicruris*) in Gaspe (Quebec) to prevent the colonization of the bryozoan fronds *Membranipora membranacea* and increase the number of annual harvests. In, pp. 1-44.

Genovesi, P. & Shine, C. (2011) European strategy on invasive alien species: Convention on the Conservation of European Wildlife and Habitats (Bern Convention). Council of Europe.

Gibbs, M.T. & Browman, H.I. (2015) Risk assessment and risk management: a primer for marine scientists. ICES Journal of Marine Science: Journal du Conseil, fsu232.

Giere, O. (2008) Meiobenthology: the microscopic motile fauna of aquatic sediments. Springer Science & Business Media.

Gilbey, V., Attrill, M.J. & Coleman, R.A. (2008) Juvenile Chinese mitten crabs (*Eriocheir sinensis*) in the Thames estuary: distribution, movement and possible interactions with the native crab *Carcinus maenas*. Biological Invasions, 10(1), 67-77.

Gíslason, Ó.S., Halldórsson, H.P., Pálsson, M.F., Pálsson, S., Davíðsdóttir, B. & Svavarsson, J. (2014) Invasion of the Atlantic rock crab (*Cancer irroratus*) at high latitudes. Biological Invasions, 16(9), 1865-1877.

Glomsrød, S. & Aslaksen, I. (2006) The economy of the North. Statistics Norway.

Goldsmit, J., Howland, K.L. & Archambault, P. (2014) Establishing a baseline for early detection of non-indigenous species in ports of the Canadian Arctic. Aquatic Invasions, 9(3), 327-342.

Gollasch, S. (2002) The importance of ship hull fouling as a vector of species introductions into the North Sea. Taylor & Francis. 105-121.

Gollasch, S., Lenz, J., Dammer, M. & Andres, H.-G. (2000) Survival of tropical ballast water organisms during a cruise from the Indian Ocean to the North Sea. Journal of Plankton Research, 22(5), 923-937.

Gomoiu, M.-T., Alexandrov, B., Shadrin, N. & Zaitsev, Y. (2002) The Black Sea—a recipient, donor and transit area for alien species. Invasive Aquatic Species of Europe. Distribution, Impacts and Management, pp. 341-350. Springer.

Goshima, S. (1982) Population dynamics of the soft clam, *Mya arenaria* L., with special reference to its life history pattern. Publication on Amakusa Marine Biological Laboratory, 6, 119-165.

Grainger, E.H. (1954) Polychaetous annelids of Ungava Bay, Hudson Strait, Frobisher Bay and Cumberland Sound. Journal of the Fisheries Board of Canada, 11(5), 507-528.

Gray, D.K., Johengen, T.H., Reid, D.F. & MacIsaac, H.J. (2007) Efficacy of open-ocean ballast water exchange as a means of preventing invertebrate invasions between freshwater ports. Limnology and Oceanography, 52(6), 2386-2397.

Griffiths, C., Robinson, T. & Mead, A. (2009) The Status and Distribution of Marine Alien Species in South Africa. Biological Invasions in Marine Ecosystems (ed. by G. Rilov and J. Crooks), pp. 393-408. Springer Berlin Heidelberg.

Grosholz, E. (2002) Ecological and evolutionary consequences of coastal invasions. Trends in Ecology & Evolution, 17(1), 22-27.

Gudimov, A.V., Gudimova, E.N. & Pavlova, L.V. (2003) Effect of the red king crab *Paralithodes camtschaticus* on the Murmansk coastal macrobenthos: the first estimates using sea urchins of the genus *Strongylocentrotus* as an example. In Doklady Biological Sciences (Vol. 393, No. 1, pp. 539-541). MAIK Nauka/Interperiodica.

Guisan, A. & Zimmermann, N.E. (2000) Predictive habitat distribution models in ecology. Ecological modelling, 135(2), 147-186.

Guisan, A., Graham, C.H., Elith, J. & Huettmann, F. (2007a) Sensitivity of predictive species distribution models to change in grain size. Diversity and Distributions, 13(3), 332-340.

Guisan, A., Zimmermann, N.E., Elith, J., Graham, C.H., Phillips, S. & Peterson, A.T. (2007b) What matters for predicting the occurrences of trees: Techniques, data, or species'characteristics? Ecological Monographs, 77(4), 615-630.

Haley, S., Klick, M., Szymoniak, N. & Crow, A. (2011) Observing trends and assessing data for Arctic mining. Polar Geography, 34(1-2), 37-61.

Harley, C.D.G., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L. & Williams, S.L. (2006) The impacts of climate change in coastal marine systems. Ecology letters, 9(2), 228-241.

Harley, C.D.G., Anderson, K.M., Lebreton, C.A.M., MacKay, A., Ayala-Díaz, M., Chong, S.L., Pond, L.M., Maddison, J.H.A., Hung, B.H.C. & Iversen, S.L. (2013) The introduction of *Littorina littorea* to British Columbia, Canada: potential impacts and the importance of biotic resistance by native predators. Marine biology, 160(7), 1529-1541.

Haugan, T.A. (2004) Bunnsamfunn og næringsvalg hos konge krabbe, *Paralithodes camtschaticus* (Tilesius, 1815), på noen lokaliteter in Finnmark. Master scient.-oppgave. Norges Fiskerihøgskole, Universitetet i Tromsø,

Hayes, K., Sliwa, C., Migus, S., McEnnulty, F. & Dunstan, P. (2005) National priority pests: Part II Ranking of Australian marine pests. Department of Environment and Heritage by CSIRO Marine Research, February. Publication at http://www.marine.csiro.au/crimp/reports/PriorityPestsFinalreport. pdf, accessed, 18, 2006.

Hayes, K.R. & Barry, S.C. (2008) Are there any consistent predictors of invasion success? Biological Invasions, 10(4), 483-506.

Hayward, P.J., Ryland, J.S., Estuarine, Coastal Sciences, A., Council, F.S. & Britain, G. (1998) Cheilostomatous bryozoa: notes for the identification of British species. Field Studies Council.

Helgason, G.V., Gardarsson, A., Svavarsson, J., Adalsteinsdottir, K. & Gudmundsson, H. (1990) Polychaetes new to the Icelandic fauna, with remarks on some previously recorded species. Sarsia, 75(3), 203-212.

Hellmann, J.J., Byers, J.E., Bierwagen, B.G. & Dukes, J.S. (2008) Five potential consequences of climate change for invasive species. Conservation biology, 22(3), 534-543.

Herborg, L.-M., Jerde, C.L., Lodge, D.M., Ruiz, G.M. & MacIsaac, H.J. (2007) Predicting invasion risk using measures of introduction effort and environmental niche models. Ecological applications, 17(3), 663-674.

Hertzog, L.R., Besnard, A. & Jay-Robert, P. (2014) Field validation shows bias-corrected pseudo-absence selection is the best method for predictive species-distribution modelling. Diversity and Distributions, 20(12), 1403-1413.

Hewitt, C.L. & Hayes, K.R. (2002) Risk assessment of marine biological invasions. Invasive aquatic species of Europe. Distribution, impacts and management, pp. 456-466. Springer.

Hewitt, C.L., Campbell, M.L. & Gollasch, S. (2006) Alien species in aquaculture: considerations for responsible use. IUCN, 32p.

Hijmans, R.J. & Graham, C.H. (2006) The ability of climate envelope models to predict the effect of climate change on species distributions. Global change biology, 12(12), 2272-2281.

Hines, A.H., Ruiz, G.M. & Fofonoff, P.W. (2000a) Summary of NIS in Prince William Sound and Alaska. In: Biological invasions of cold-water coastal ecosystems: ballast-mediated introductions in Port Valdez / Prince William Sound, Alaska., p. 26. Regional Citizens' Advisory Council of Prince William Sound, Prince William Sound.

Hines, A.H., Ruiz, G.M., Chapman, J., Hansen, G.I., Carlton, J.T., Foster, N. & Feder, H. (2000b) Biological invasions of cold-water coastal ecosystems: ballast-mediated introductions in Port Valdez/Prince William Sound, Alaska. Final Report to Regional Citizens Advisory Council of Prince William Sound, 340.

Hoegh-Guldberg, O. & Bruno, J.F. (2010) The impact of climate change on the world's marine ecosystems. Science, 328(5985), 1523-1528.

Holland, M.M., Bitz, C.M. & Tremblay, B. (2006) Future abrupt reductions in the summer Arctic sea ice. Geophysical Research Letters, 33(23).

Hu, X. & Myers, P.G. (2014) Changes to the Canadian Arctic Archipelago Sea Ice and Freshwater Fluxes in the Twenty-First Century under the Intergovernmental Panel on Climate Change A1B Climate Scenario. Atmosphere-Ocean, 52(4), 331-350.

Hutchinson, G.E. (1957) Cold spring harbor symposium on quantitative biology. Concluding remarks. Cold Spring Harbor Laboratory Press.

Inglis, G., Gust, N., Fitridge, I., Floerl, O., Woods, C., Hayden, B. & Fenwick, G. (2006) Port of Timaru. Baseline survey for non-indigenous marine species. New Zealand, 93p.

IPCC (2001) Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC (2007) Climate change 2007: impacts, adaptation, and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Iwasaki, K. (2006) Human-mediated introduction of marine organisms in Japan: a review. Assessment and Control of Biological Invasion Risks. Shoukadoh Book Sellers, Kyoto, Japan and IUCN, Gland, Switzerland, 104-112.

Jacobs, J.D. & Stenton, D.R. (1985) Environment, resources, and prehistoric settlement in upper Frobisher Bay, Baffin Island. Arctic Anthropology, 59-76.

Jiménez-Valverde, A. & Lobo, J.M. (2007) Threshold criteria for conversion of probability of species presence to either–or presence–absence. Acta oecologica, 31(3), 361-369.

Jirkov, I.A. & Leontovich, M.K. (2012) Biogeography of Polychaeta of the Eurasian North Polar Basin. Invertebrate Zoology, 9(1), 41.

Johannesson, K. (1988) The paradox of Rockall: why is a brooding gastropod (*Littorina saxatilis*) more widespread than one having a planktonic larval dispersal stage (*L. littorea*)? Marine Biology, 99(4), 507-513.

Jørgensen, L.L. (2005) Impact scenario for an introduced decapod on Arctic epibenthic communities. Biological Invasions, 7(6), 949-957.

Jørgensen, L.L. & Nilssen, E.M. (2011) The invasive history, impact and management of the red king crab *Paralithodes camtschaticus* off the coast of Norway. In the Wrong Place-Alien Marine Crustaceans: Distribution, Biology and Impacts, pp. 521-536. Springer.

Kaluza, P., Kölzsch, A., Gastner, M.T. & Blasius, B. (2010) The complex network of global cargo ship movements. Journal of the Royal Society Interface, 7(48), 1093-1103.

Kelley, A., de Rivera, C. & Buckley, B. (2013) Cold tolerance of the invasive *Carcinus maenas* in the east Pacific: molecular mechanisms and implications for range expansion in a changing climate. Biological Invasions, 15(10), 2299-2309.

Kenchington, E., Link, H., Roy, V., Archambault, P., Siferd, T., Treble, M., Wareham, V., Department of, F., Oceans, O.O.N. & Canadian Science Advisory Secretariat, O.O.N. (2011) Identification of mega- and macrobenthic ecologically and biologically significant areas (EBSAs) in the Hudson Bay Complex, the western and eastern Canadian Arctic. In. DFO, Ottawa, ON(Canada)

Kennedy, T.A., Naeem, S., Howe, K.M., Knops, J.M.H., Tilman, D. & Reich, P. (2002) Biodiversity as a barrier to ecological invasion. Nature, 417(6889), 636-638.

Kennedy, V.S. (1985) A summer benthic survey in Conception Bay, Newfoundland, emphasizing zoogeography of annelids and amphipods. Canadian journal of zoology, 63(8), 1863-1869.

Klassen, G.J. & Locke, A. (2007) A biological synopsis of the European green crab, *Carcinus maenas*. p. vii+75pp. Canadian Manuscript Report of Fisheries and Aquatic Sciences

Kluge, G.A. (1975) Bryozoa of the northern seas of the USSR= Mshanki severnykh morei SSSR.

Knight-Jones, P., Knight-Jones, E.W. & Buzhinskaya, G. (1991) Distribution and interrelationships of northern spirorbid genera. Bulletin of Marine Science, 48(2), 189-197.

Koh, B.S. & Bhaud, M.R. (2003) Identification of new criteria for differentating between populations of *Owenia fusiformis* (Annelida polychaeta) from different origins: Rehabilitation of old species and erection of new species. Vie et milieu, 53(2-3), 65-95.

Kolar, C.S. & Lodge, D.M. (2002) Ecological predictions and risk assessment for alien fishes in North America. Science, 298(5596), 1233-1236.

Kumschick, S. & Richardson, D.M. (2013) Species-based risk assessments for biological invasions: advances and challenges. Diversity and Distributions, 19(9), 1095-1105.

Kumschick, S., Gaertner, M., Vilà, M., Essl, F., Jeschke, J.M., Pyšek, P., Ricciardi, A., Bacher, S., Blackburn, T.M. & Dick, J.T.A. (2015) Ecological impacts of alien species: quantification, scope, caveats, and recommendations. BioScience, 65(1), 55-63.

Lambert, G., Shenkar, N. & Swalla, B.J. (2010) First Pacific record of the north Atlantic ascidian *Molgula citrina*-bioinvasion or circumpolar distribution. Aquatic Invasions, 5(4), 369-378.

Larsen, J.N., Anisimov O. A., Constable A., Hollowed A., Maynard N., Prestrud P. , Prowse T. & J., S. (2014) Polar Regions. In: Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Lassuy, D.R. & Lewis, P.N. (2013) Invasive species: human-induced. Conservation of Arctic Flora and Fauna and Arctic Council. Available http://www. arcticbiodiversity. is/index. php/the-report. Last visited, October 2014.

Lawrence, M. & Baker, R. (1995) Biological survey of the Churchill River Estuary. A report prepared for Manitoba Hydro by North/South Consultants Inc., Winnipeg, Manitoba, 30p.

Leppäkoski, E. & Olenin, S. (2000) Non-native species and rates of spread: lessons from the brackish Baltic Sea. Biological invasions, 2(2), 151-163.

Leppäkoski, E.J. (1991) Introduced species—resource or threat in brackish-water seas? Examples from the Baltic and the Black Sea. Marine Pollution Bulletin, 23, 219-223.

Levings, C.D., Cordell, J.R., Ong, S. & Piercey, G.E. (2004) The origin and identity of invertebrate organisms being transported to Canada's Pacific coast by ballast water. Canadian Journal of Fisheries and Aquatic Sciences, 61(1), 1-11.

Liu, C., White, M. & Newell, G. (2013) Selecting thresholds for the prediction of species occurrence with presence-only data. Journal of Biogeography, 40(4), 778-789.

Lobo, J.M. (2008) More complex distribution models or more representative data? Biodiversity Informatics, 5

Locke, A. (2009) A screening procedure for potential tunicate invaders of Atlantic Canada. Aquatic Invasions, 4(1), 71-79.

Locke, A. & Hanson, J.M. (2009) Rapid response to nonindigenous species. 3. A proposed framework. Aquatic Invasions, 4(1), 259-273).

Locke, A., Reid, D.M., van Leeuwen, H.C., Sprules, W.G. & Carlton, J.T. (1993) Ballast Wafer Exchange as a Means of Controlling Dispersal of Freshwater Organisms by Ships. Canadian Journal of Fisheries and Aquatic Sciences, 50(10), 2086-2093.

Locke, A., Hanson, J.M., Ellis, K.M., Thompson, J. & Rochette, R. (2007) Invasion of the southern Gulf of St. Lawrence by the clubbed tunicate (*Styela clava* Herdman): Potential mechanisms for invasions of Prince Edward Island estuaries. Journal of Experimental Marine Biology and Ecology, 342(1), 69-77.

Lockwood, J.L., Cassey, P. & Blackburn, T. (2005) The role of propagule pressure in explaining species invasions. Trends in Ecology & Evolution, 20(5), 223-228.

Lockwood, J.L., Hoopes, M.F. & Marchetti, M.P. (2007) Invasion ecology. John Wiley & Sons, 304p.

Lockwood , J.L., Cassey, P. & Blackburn, T.M. (2009) The more you introduce the more you get: the role of colonization and propagule pressure in invasion ecology. Diversity and Distributions 15, 904-910.

Lowe, S., Browne, M., Boudjelas, S. & De Poorter, M. (2000) 100 of the world's worst invasive alien species: a selection from the global invasive species database. Invasive Species Specialist Group Species Survival Commission, World Conservation Union (IUCN), Auckland, New Zealand.

Lowry, J.K. & Stoddart, H.E. (1993) The *Onisimus* problem (Amphipoda, Lysianassoidea, Uristidae). Zoologica scripta, 22(2), 167-181.

MacArthur, R. (1970) Species packing and competitive equilibrium for many species. Theoretical population biology, 1(1), 1-11.

MacDonald, I.R., Bluhm, B.A., Iken, K., Gagaev, S. & Strong, S. (2010) Benthic macrofauna and megafauna assemblages in the Arctic deep-sea Canada Basin. Deep Sea Research Part II: Topical Studies in Oceanography, 57(1), 136-152.

MacIsaac, H.J., Robbins, T.C. & Lewis, M.A. (2002) Modeling ships' ballast water as invasion threats to the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences, 59(7), 1245-1256.

Madec, G. (2008) NEMO ocean engine.

Mandrak, N.E. & Cudmore, B. (2015) Risk Assessment: Cornerstone of an Aquatic Invasive Species Program. Aquatic Ecosystem Health & Management, (accepted).

Mandrak, N.E., Cudmore, B. & Chapman, P.M. (2012) National detailed-level risk assessment guidelines: assessing the biological risk of aquatic invasive species in Canada. In: Canadian Science Advisory Secretariat, Ottawa O. N. Department of, Fisheries Oceans, Ottawa O. N.

Marbuah, G., Gren, I.-M. & McKie, B. (2014) Economics of Harmful Invasive Species: A Review. Diversity, 6(3), 500-523.

Mathieson, A.C., Moore, G.E. & Short, F.T. (2010) A floristic comparison of seaweeds from James Bay and three contiguous northeastern Canadian Arctic sites. Rhodora, 112(952), 396-434.

Mathieson, A.C., Pederson, J.R., Neefus, C.D., Dawes, C.J. & Bray, T.L. (2008) Multiple assessments of introduced seaweeds in the Northwest Atlantic. ICES Journal of Marine Science: Journal du Conseil, 65(5), 730-741.

McCollin, T., Shanks, A.M. & Dunn, J. (2008) Changes in zooplankton abundance and diversity after ballast water exchange in regional seas. Marine Pollution Bulletin, 56(5), 834-844.

McPherson, E. (1971) The marine molluscs of Arctic Canada: Prosobranch gastropods, chitons, and scaphopods. Natural Museum Canadian Public Biology and Oceanography, 3, 1-149.

Meier, W.N., Hovelsrud, G.K., Oort, B.E.H., Key, J.R., Kovacs, K.M., Michel, C., Haas, C., Granskog, M.A., Gerland, S. & Perovich, D.K. (2014) Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity. Reviews of Geophysics, 52(3), 185-217.

Meier, W. & Stroeve, J. (2015) National Snow and Ice Data Center http://nsidc.org/arcticseaicenews/. Accessed on January 2016.

Merow, C., Smith, M.J. & Silander, J.A. (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography, 36(10), 1058-1069.

Miller, A.W. & Ruiz, G.M. (2014) Arctic shipping and marine invaders. Nature Climate Change, 4(6), 413-416.

Minchin, D. (2006) The transport and the spread of living aquatic species. The Ecology of Transportation: Managing Mobility for the Environment (ed. by J. Davenport and J. Davenport), pp. 77-97. Springer Netherlands.

Minchin, D., Gollasch, S., Cohen, A.N., Hewitt, C.L. & Olenin, S. (2009) Characterizing vectors of marine invasion. Biological invasions in marine ecosystems, pp. 109-116. Springer.

Molnar, J.L., Gamboa, R.L., Revenga, C. & Spalding, M.D. (2008) Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment, 6(9), 485-492.

Moore, A.M., Vercaemer, B., DiBacco, C., Sephton, D. & Ma, K.C.K. (2014) Invading Nova Scotia: first records of *Didemnum vexillum* Kott, 2002 and four more non-indigenous invertebrates in 2012 and 2013. BioInvasions Records, 3(4), 225-234.

Mora, C., Tittensor, D.P., Adl, S., Simpson, A.G.B. & Worm, B. (2011) How many species are there on Earth and in the ocean? Plos One Biol, 9 (8)

Morgan, R.P., Block, S.B., Ulanowicz, N.I. & Buys, C. (1978) Genetic variation in the soft-shelled clam, *Mya arenaria*. Estuaries, 1(4), 255-258.

Moss, R.H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J.A., Elgizouli, I., Emori, S., Lin, E. & Hibbard, K. (2008) Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. Pacific Northwest National Laboratory (PNNL), Richland, WA (US)

Murphy, D.J. (1979) A Comparative Study of the Freezing Tolerances of the Marine Snails *Littorina littorea* (L.) and *Nassarius obsoletus* (Say). Physiological Zoology, 52, 219-230.

Naumov, D.V. (1969) Hydroids and Hydromedusae of the USSR. Israel Program for Scentific Translations.

Niimi, A.J. (2004) Environmental and economic factors can increase the risk of exotic species introductions to the Arctic region through increased ballast water discharge. Environmental Management, 33(5), 712-718.

NISC (2003) United States National Invasive Species Council. General guidelines for the establishment and evaluation of invasive species early detection and rapid response systems. Available at: https://www.doi.gov/invasivespecies (accessed 2013).

Nishikawa, T. (1991) The ascidians of the Japan Sea. II. Publications of the Seto marine biological Laboratory, 35, 25-170.

NMNH (2012) Canadian Invertebrates. In, National Museum of Natural History. Smithsonian Institution Holdings,.

NOAA (2015) National Oceanic and Atmospheric Administration. Available at: http://www.noaa.gov/ (accessed 31st August 2015).

NSIDC (2012) National Snow and Ice Data Center. Available at: http://nsidc.org (accessed March 2012).

NSIDC (2015) National Snow and Ice Data Center. Available at: http://nsidc.org/arcticseaicenews/tag/maximum/ (accessed 31st August 2015).

OBIS (2013) The Ocean Biogeographic Information System. Available at: http://www.iobis.org (accessed June-August 2013).

Obolewski, K. & Piesik, Z. (2005) *Mya arenaria* (L.) in the Polish Baltic Sea Coastal (Kołobrzeg-Władysławowo). Baltic Coastal Zone, 9, 13-27.

Occhipinti-Ambrogi, A. (2007) Global change and marine communities: alien species and climate change. Marine pollution bulletin, 55(7), 342-352.

Olivier, F., San Martín, G. & Archambault, P. (2013) A new species of *Streptospinigera* Kudenov, 1983 (Polychaeta, Syllidae, Anoplosyllinae) from the Arctic and north-western Atlantic with a key to all species of the genus. Polar biology, 36(10), 1499-1507.

Orlov, Y.I. & Ivanov, B.G. (1978) On the introduction of the Kamchatka king crab *Paralithodes camtschatica* (Decapoda: Anomura: Lithodidae) into the Barents Sea. Marine Biology, 48(4), 373-375.

Osburn, R.C. (1932) Biological and Oceanographic Conditions in Hudson Bay. Bryozoa from Hudson Bay and Strait. Contributions to Canadian Biology and Fisheries, 7(1), 361-376.

Oug, E. (2011) Guide to identification of Lumbrineridae (Polychaeta) in Norwegian and adjacent waters.

Oug, E., Cochrane, S.K.J., Sundet, J.H., Norling, K. & Nilsson, H.C. (2011) Effects of the invasive red king crab (*Paralithodes camtschaticus*) on soft-bottom fauna in Varangerfjorden, northern Norway. Marine Biodiversity, 41(3), 467-479.

Palomares, M. & Pauly, D. (2013) SeaLifeBase, World Wide Web electronic publication. Available at: http://www.sealifebase.org, (accessed June-August 2013)

Pavlova, L.V., Britayev, T.A. & Rzhavsky, A.V. (2007) Benthos elimination by juvenile red king crabs *Paralithodes camtschaticus* (Tilesius, 1815) in the Barents Sea coastal zone: Experimental data. In Doklady Biological Sciences, 414(1), 231-234. MAIK Nauka/Interperiodica.

Pavlova, L.V., Kuzmin, S.A., Rzhavsky, A.V. & Britayev, T.A. (2004) On the biology and feeding of the juvenile red king crab *Paralithodes camtschaticus* from Dal'nezelenetskaya Bay (Barents Sea). Shelf zoobenthos Investigations. Information support of the ecosystem investigations. GG Matishov (Ed.). KSC Press, Apatity, Russia, 49-95.

Pearse, V.B. & Pearse, J.S. (1991) Year-long settling plate study yields no Antarctic placozoans, and surprisingly little else. Antarctic J US, 26, 149-150.

Pearson, R.G. & Dawson, T.P. (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography, 12(5), 361-371.

Pearson, R.G., Raxworthy, C.J., Nakamura, M. & Townsend Peterson, A. (2007) Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. Journal of Biogeography, 34(1), 102-117.

Petersen, G.H. (1999) Five recent *Mya* species, including three new species and their fossil connections. Polar Biology, 22(5), 322-328.

Petersen, J.K., Hansen, J.W., Laursen, M.B., Clausen, P., Carstensen, J. & Conley, D.J. (2008) Regime shift in a coastal marine ecosystem. Ecological Applications, 18(2), 497-510.

Peterson, A.T. (2003) Predicting the geography of species' invasions via ecological niche modeling. The Quarterly review of biology, 78(4), 419-433.

Petraitis, P.S. (1987) Factors organizing rocky intertidal communities of New England: herbivory and predation in sheltered bays. Journal of Experimental Marine Biology and Ecology, 109(2), 117-136.

Pettibone, M.H. (1956) Marine polychaete worms from Labrador.

Pettibone, M.H. (1992) Contribution to the polychaete family Pholoidae Kinberg. Smithsonian Institution Press.

Phillips, S.J. & Dudík, M. (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography, 31(2), 161-175.

Phillips, S.J., Anderson, R.P. & Schapire, R.E. (2006) Maximum entropy modeling of species geographic distributions. Ecological modelling, 190(3), 231-259.

Phillips, S.J., Dudík, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J. & Ferrier, S. (2009) Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. Ecological Applications, 19(1), 181-197.

Piepenburg, D. (2005) Recent research on Arctic benthos: common notions need to be revised. Polar Biology, 28(10), 733-755.

Piepenburg, D., Archambault, P., Ambrose Jr, W.G., Blanchard, A.L., Bluhm, B.A., Carroll, M.L., Conlan, K.E., Cusson, M., Feder, H.M. & Grebmeier, J.M. (2011) Towards a pan-Arctic inventory of the species diversity of the macro-and megabenthic fauna of the Arctic shelf seas. Marine Biodiversity, 41(1), 51-70.

Pimentel, D., McNair, S., Janecka, J., Wightman, J., Simmonds, C., O'connell, C., Wong, E., Russel, L., Zern, J. & Aquino, T. (2001) Economic and environmental threats of alien plant, animal, and microbe invasions. Agriculture, Ecosystems & Environment, 84(1), 1-20.

Pizzolato, L., Howell, S.E.L., Derksen, C., Dawson, J. & Copland, L. (2014) Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change, 123(2), 161-173.

Pocklington, P. (1989) Polychaetes of eastern Canada: An illustrated key to polychaetes of eastern Canada including the eastern Arctic. Ottawa: Department of Fisheries and Oceans.

Powell, N.A. (1968) Bryozoa (Polyzoa) of Arctic Canada. Journal of the Fisheries Board of Canada, 25(11), 2269-2320.

Pulliam, H.R. (2000) On the relationship between niche and distribution. Ecology letters, 3(4), 349-361.

Rainer, S.F. (1984) *Nephtys pente* sp. nov.(Polychaeta: Nephtyidae) and a key to *Nephtys* from northern Europe. Journal of the Marine Biological Association of the United Kingdom, 64(04), 899-907.

Ramos, J., San Martín, G. & Sikorski, A. (2010) Syllidae (Polychaeta) from the Arctic and sub-Arctic regions. Journal of the Marine Biological Association of the United Kingdom, 90(5), 1041-1050.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. & Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research: Atmospheres (1984–2012), 108(D14).

Reid, D.G. (1996) Systematics and evolution of *Littorina*. Ray society London.

Reiss, H., Birchenough, S., Borja, A., Buhl-Mortensen, L., Craeymeersch, J., Dannheim, J., Darr, A., Galparsoro, I., Gogina, M. & Neumann, H. (2014) Benthos distribution modelling and its relevance for marine ecosystem management. ICES Journal of Marine Science: Journal du Conseil, fsu107.

Renaud, P.E., Sejr, M.K., Bluhm, B.A., Sirenko, B. & Ellingsen, I.H. (2015) The future of Arctic benthos: expansion, invasion, and biodiversity. Progress in Oceanography (accepted).

Ricciardi, A. (2006) Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Diversity and Distributions, 12(4), 425-433.

Ricciardi, A. & Rasmussen, J.B. (1998) Predicting the identity and impact of future biological invaders: A priority for aquatic resource management. Canadian Journal of Fisheries and Aquatic Sciences, 55(7), 1759-1765.

Ricciardi, A., Hoopes, M.F., Marchetti, M.P. & Lockwood, J.L. (2013) Progress toward understanding the ecological impacts of nonnative species. Ecological Monographs, 83(3), 263-282.

Richardson, A.J. & Poloczanska, E.S. (2008) Under-resourced, under threat. Science-New York then Washington, 320(5881), 1294.

Rilov, G. & Crooks, J.A. (2008) Biological invasions in marine ecosystems: ecological, management, and geographic perspectives. Springer Science & Business Media, 625p.

Robinson, L.M., Elith, J., Hobday, A.J., Pearson, R.G., Kendall, B.E., Possingham, H.P. & Richardson, A.J. (2011) Pushing the limits in marine species distribution modelling:

lessons from the land present challenges and opportunities. Global Ecology and Biogeography, 20(6), 789-802.

Rodin, V.E. (1989) Population biology of the king crab *Paralithodes camtschatica* Tilesius in the North Pacific Ocean. In BR Melteff, Coordinator. Proceedings of the international symposium on king and Tanner crabs. Report AK-SG-90-04. University of Alaska Sea Grant Program, Anchorage, Alaska, USA p. 133-144.

Roy, V., Iken, K. & Archambault, P. (2014) Environmental Drivers of the Canadian Arctic Megabenthic Communities. PloS one, 9, e100900.

Ruffilli, D.C. (2011) Arctic Marine and Intermodal Infrastructure: Challenges and the Government of Canada's Response. Library of Parliament.

Ruiz, G.M. & Carlton, J.T. (2003) Invasion vectors: a conceptual framework for management. Invasive species: vectors and management strategies, 459-504.

Ruiz, G.M. & Smith, G. (2005) Biological study of container vessels at the Port of Oakland. Final report.

Ruiz, G.M. & Reid, D.F. (2007) Current state of understanding about the effectiveness of ballast water exchange (BWE) in reducing aquatic nonindigenous species (ANS) introductions to the Great Lakes Basin and Chesapeake Bay, USA: synthesis and analysis of existing information. US Department of Commerce, National Oceanic and Atmospheric Administration.

Ruiz, G.M. & Hewitt, C.L. (2009) Latitudinal patterns of biological invasions in marine ecosystems: a polar perspective. Smithsonian Institution Scholarly Press, Washington DC, 347-358.

Ruiz, G.M., Carlton, J.T., Grosholz, E.D. & Hines, A.H. (1997) Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. American Zoologist, 37, 621-632.

Ruiz, G.M., Fofonoff, P.W., Steves, B.P. & Carlton, J.T. (2015) Invasion history and vector dynamics in coastal marine ecosystems: A North American perspective. Aquatic Ecosystem Health & Management, (accepted).

Ruiz, G.M., Fofonoff, P.W., Carlton, J.T., Wonham, M.J. & Anson, H.H. (2000) Invasion of Coastal Marine Communities in North America: Apparent Patterns, Processes, and Biases. Annual Review of Ecology and Systematics, 31, 481-531.

Ruiz, G.M., Huber, T., Larson, K., McCann, L., Steves, B., Fofonoff, P. & Hines, A.H. (2006) Biological Invasions in Alaska's Coastal Marine Ecosystems: Establishing a

Baseline. Prince William Sound Regional Citizens' Advisory Council & U.S. Fish & Wildlife Service, Prince William Sound, 112p.

Samuelson, G.M. (2001) Polychaetes as indicators of environmental disturbance on subarctic tidal flats, Iqaluit, Baffin Island, Nunavut Territory. Marine pollution bulletin, 42(9), 733-741.

Saucier, F.J., Senneville, S., Prinsenberg, S., Roy, F., Smith, G., Gachon, P., Caya, D. & Laprise, R. (2004) Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada. Climate Dynamics, 23(3-4), 303-326.

Saunders, M. & Metaxas, A. (2007) Temperature explains settlement patterns of the introduced bryozoan *Membranipora membranacea* in Nova Scotia, Canada. Marine Ecology, Progress Series, 344, 95-106.

Saunders, M. & Metaxas, A. (2008) High recruitment of the introduced bryozoan *Membranipora membranacea* is associated with kelp bed defoliation in Nova Scotia, Canada. Marine Ecology-Progress Series, 369, 139-151.

Schoener, A., Long, E.R. & DePalma, J.R. (1978) Geographic variation in artificial island colonization curves. Ecology, 367-382.

Schultz, M.P., Bendick, J.A., Holm, E.R. & Hertel, W.M. (2011) Economic impact of biofouling on a naval surface ship. Biofouling, 27(1), 87-98.

Schwaninger, H.R. (1999) Population structure of the widely dispersing marine bryozoan *Membranipora membranacea* (Cheilostomata): implications for population history, biogeography, and taxonomy. Marine Biology, 135(3), 411-423.

Séguin, E., Sawada, M. & Wilson, K. (2005) Extending Churchills shipping season using GIS based modeling. Proceedings of the 98th Annual Canadian Institute of Geomatics Conferences, University of Ottawa, Canada.

Simard, N. & Hardy, M. (2004) The Laurentian Channel as an alternative ballast water exchange zone: risks, analysis and recommendations. Fisheries and Oceans.

Simard, N., Plourde, S., Gilbert, M. & Gollasch, S. (2011) Net efficacy of open ocean ballast water exchange on plankton communities. Journal of Plankton Research, 33(9), 1378-1395.

Simkanin, C., Davidson, I.C., Dower, J.F., Jamieson, G. & Therriault, T.W. (2012) Anthropogenic structures and the infiltration of natural benthos by invasive ascidians. Marine Ecology, 33(4), 499-511.

Sirenko, B.I., Clarke, C., Hopcroft, R.R., Huettmann, F., Bluhm, B.A. & Gradinger, R. (2010) The Arctic register of marine species (ARMS) compiled by the Arctic Ocean Diversity (ArcOD) project.

Smith, C.R., Grange, L.J., Honig, D.L., Naudts, L., Huber, B., Guidi, L. & Domack, E. (2011) A large population of king crabs in Palmer Deep on the west Antarctic Peninsula shelf and potential invasive impacts. Proceedings of the Royal Society of London B: Biological Sciences, rspb20111496.

Smith, L.C. & Stephenson, S.R. (2013) New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sicences, 110(13), E1191-E1195.

Snelgrove, P.V.R., Archambault, P., Juniper, S.K., Lawton, P., Metaxas, A., Pepin, P., Rice, J.C. & Tunnicliffe, V. (2012) Canadian Healthy Oceans Network (CHONe): An Academic–Government Partnership to Develop Scientific Guidelines for Conservation and Sustainable Usage of Marine Biodiversity. Fisheries, 37(7), 296-304.

Solomon, S. (2007) Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Cambridge University Press.

Sorte, C.J.B., Williams, S.L. & Zerebecki, R.A. (2010) Ocean warming increases threat of invasive species in a marine fouling community. Ecology, 91(8), 2198-2204.

Southward, A.J. (1957) On the behaviour of barnacles III. Further observations on the influence of temperature and age on cirral activity. Journal of the Marine Biological Association of the United Kingdom, 36(02), 323-334.

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M.A.X., Halpern, B.S., Jorge, M.A., Lombana, A.L. & Lourie, S.A. (2007) Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. BioScience, 57(7), 573-583.

Stachowicz, J.J., Terwin, J.R., Whitlatch, R.B. & Osman, R.W. (2002a) Linking climate change and biological invasions: ocean warming facilitates nonindigenous species invasions. Proceedings of the National Academy of Sciences, 99(24), 15497-15500.

Stachowicz, J.J., Fried, H., Osman, R.W. & Whitlatch, R.B. (2002b) Biodiversity, invasion resistance, and marine ecosystem function: reconciling pattern and process. Ecology, 83(9), 2575-2590.

Stebbing, T. (1906) Amphipoda I. Gammaridea, 785p.

Stephenson, S.A. & Hartwig, L. (2010) The Arctic Marine Workshop: Freshwater Institute Winnipeg, Manitoba. Canadian Manuscript Report of Fisheries and Aquatic Sciencie 2934: vi+67p.

Stewart, P.L., Pocklington, P. & Cunjak, R.A. (1985) Distribution, abundance and diversity of benthic macroinvertebrates on the Canadian continental shelf and slope of southern Davis Strait and Ungava Bay. Arctic, 281-291.

Strasser, M. (1998) *Mya arenaria*—an ancient invader of the North Sea coast. Helgoländer Meeresuntersuchungen, 52(3-4), 309-324.

Strayer, D.L. (2012) Eight questions about invasions and ecosystem functioning. Ecology Letters, 15(10), 1199-1210.

Streftaris, N., Zenetos, A. & Papathanassiou, E. (2005) Globalisation in marine ecosystems: the story of non-indigenous marine species across European seas. Oceanography and Marine Biology: An Annual Review, 43, 419-453.

Strelzov, V.E. (1979) Polychaete worms of the family Paraonidae Cerruti, 1909.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T. & Serreze, M. (2007) Arctic sea ice decline: Faster than forecast. Geophysical Research Letters, 34(9)

Stroeve, J., Serreze, M., Holland, M., Kay, J., Malanik, J. & Barrett, A. (2012) The Arctic's rapidly shrinking sea ice cover: a research synthesis. Climatic Change, 110(3-4), 1005-1027.

Svavarsson, J. & Dungal, P. (2008) Leyndardómar sjávarins við Ísland, Reykjavík.

Sylvester, F., Kalaci, O., Leung, B., Lacoursière-Roussel, A., Murray, C.C., Choi, F.M., Bravo, M.A., Therriault, T.W. & MacIsaac, H.J. (2011) Hull fouling as an invasion vector: can simple models explain a complex problem? Journal of Applied Ecology, 48(2), 415-423.

Tang, C.L., Yao, T., Perrie, W., Detracey, B.M., Toulany, B., Dunlap, E. & Wu, Y. (2008) BIO ice-ocean and wave forecasting models and systems for Eastern Canadian waters. Fisheries and Oceans Canada.

Therriault, T.W., Herborg, L.M., Locke, A. & McKindsey, C.W. (2008) Risk assessment for European green crab (*Carcinus maenas*) in Canadian waters. Canadian Science Advisory Secretariat 2008/042, Department of Fisheries Oceans, Ottawa O. N.

Thomson, D.H., Martin, C.M. & Cross, W.E. (1986) Identification and characterization of arctic nearshore benthic habitats. Fisheries and Oceans, Canada, Canada. Dept. of, Fisheries Oceans. Western, Region.

Thorson, G. (1950) Reproductive and larval ecology of marine bottom invertebrates. Biological reviews, 25(1), 1-45.

Thorson, G. & Jørgensen, C.B. (1946) Reproduction and Larval Development Fo Danish Marine Bottom Invertebrates, with Special Reference to the Planktonic Larvae in the Sound (Øresund).: With a Section on Lamellibranch Larvae. Reitzel.

Thresher, R.E. & Kuris, A.M. (2004) Options for managing invasive marine species. Biological Invasions, 6(3), 295-300.

Tilman, D. (1999) The ecological consequences of changes in biodiversity: A search for general principles 101. Ecology, 80(5), 1455-1474.

Transport_Canada (2007) A guide to Canada's ballast water control and management regulations. Environmental Protection. Transport Canada, Ottawa, TP 13617E

Turcotte, C. & Sainte-Marie, B. (2009) Biological synopsis of the Japanes skeleton shrimp (*Caprella mutica*). Fisheries and Oceans, Canada. Canadian Manuscript Report on Fisheries and Aquatic Sciences 2903, p. vii + 26.

Tyberghein, L., Verbruggen, H., Pauly, K., Troupin, C., Mineur, F. & De Clerck, O. (2012) Bio-ORACLE: a global environmental dataset for marine species distribution modelling. Global Ecology and Biogeography, 21(2), 272-281.

Tyrrell, M.C., Dionne, M. & Edgerly, J.A. (2008) Physical factors mediate effects of grazing by a non-indigenous snail species on saltmarsh cordgrass (Spartina alterniflora) in New England marshes. ICES Journal of Marine Science: Journal du Conseil, 65(5), 746-752.

Vader, W., Johnsen, J.R. & Berge, J. (2005) Studies on the genus *Onisimus* Boeck, 1871 (Crustacea, Amphipoda, Lysianassoidea, Uristidae) Part I. The *brevicaudatus* and *sextonae* species groups. Organisms Diversity & Evolution, 5(2), 161-164.

Valle, M., Chust, G., del Campo, A., Wisz, M.S., Olsen, S.M., Garmendia, J.M. & Borja, Á. (2014) Projecting future distribution of the seagrass *Zostera noltii* under global warming and sea level rise. Biological Conservation, 170, 74-85.

Van Name, W.G. (1945) The north and south American ascidians. Bulletin of the American Museum of Natural History, 84, 1– 476.

Veldhuizen, T.C. & Stanish, S. (1999) Overview of the life history, distribution, abundance, and impact of the Chinese mitten crab. *Eriocheir sinensis*. Submitted to the Aquatic Nuisance Task Force, 114p.

Verling, E., Ruiz, G.M., Smith, L.D., Galil, B., Miller, A.W. & Murphy, K.R. (2005) Supply-side invasion ecology: characterizing propagule pressure in coastal ecosystems. Proceedings of the Royal Society of London B: Biological Sciences, 272(1569), 1249-1257.

Vermeij, G.J. & Roopnarine, P.D. (2008) The coming Arctic invasion. Science, 321(5890), 780-781.

Vilà, M., Basnou, C., Pyšek, P., Josefsson, M., Genovesi, P., Gollasch, S., Nentwig, W., Olenin, S., Roques, A. & Roy, D. (2009) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. Frontiers in Ecology and the Environment, 8(3), 135-144.

Villac, M.C. & Kaczmarska, I. (2011) Estimating propagule pressure and viability of diatoms detected in ballast tank sediments of ships arriving at Canadian ports. Marine Ecology Progress Series, 425, 47-61.

Villac, M.C., Persich, G., Fernandes, L., Paranhos, R., Bonecker, S., Garcia, V., Odebrecht, C., Tenenbaum, D., Tristao, M.L. & de Andrade, S. (2000) Ballast water exchange: testing the dilution method. Harmful algal blooms, 470-473.

Villarino, E., Chust G., Licandro P., Butenschön M., Ibaibarriaga L., Larrañaga A. & X., I. (2015) Modelling the future biogeography of North Atlantic zooplankton communities in response to climate change. Marine Ecology Progress Series, Ms. No. 201409009, (accepted).

Wacasey, J.W. (1975) Biological productivity of the southern Beaufort Sea: zoobenthic studies. Beaufort Sea Project.

Wacasey, J.W. (1979) Zoobenthos data from upper Frobisher Bay, 1967-1973. Arctic Biological Station, Department of Fisheries and Oceans.

Wacasey, J.W., Atkinson, E.G. & Kinlough, L. (1976) Zoobenthos data from James Bay, 1956-1974. Fisheries and Marine Services Research and Development Technical Report

Wacasey, J.W., Atkinson, E.G., Glasspoole, L. & Station, A.B. (1980) Zoobenthos data from inshore stations of upper Frobisher Bay, 1969-1976. Arctic Biological Station, Department of Fisheries and Oceans.

Walsh, J.E., Overland, J.E., Groisman, P.Y. & Rudolf, B. (2011) Ongoing climate change in the Arctic. Ambio, 40(1), 6-16.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Guldberg, O. & Bairlein, F. (2002) Ecological responses to recent climate change. Nature, 416(6879), 389-395.

Walther, G.-R., Roques, A., Hulme, P.E., Sykes, M.T., Pyšek, P., Kühn, I., Zobel, M., Bacher, S., Botta-Dukát, Z. & Bugmann, H. (2009) Alien species in a warmer world: risks and opportunities. Trends in ecology & evolution, 24(12), 686-693.

Wang, M. & Overland, J.E. (2009) A sea ice free summer Arctic within 30 years? Geophysical Research Letters, 36(7).

Ware, C., Berge, J., Sundet, J.H., Kirkpatrick, J.B., Coutts, A.D.M., Jelmert, A., Olsen, S.M., Floerl, O., Wisz, M.S. & Alsos, I.G. (2014) Climate change, non-indigenous species and shipping: assessing the risk of species introduction to a high-Arctic archipelago. Diversity and Distributions, 20(1), 10-19.

Ware, C.J. (2014) Measuring and managing invasive species threats in the Arctic. (Doctoral dissertation University of Tasmania).

Washington_Post (2015) The Arctic has lost so much ice that now people want to race yachts through it. Available at: http://www.washingtonpost.com/news/energy-environment/wp/2015/04/08/the-arctic-has-melted-so-much-that-people-want-to-race-yachts-through-the-northwest-passage/ (accessed August 31st 2015).

Wassmann, P. (2015) Overarching perspectives of contemporary and future ecosystems in the Arctic Ocean. Progress in Oceanography (accepted).

Wassmann, P., Duarte, C.M., Agusti, S. & Sejr, M.K. (2011) Footprints of climate change in the Arctic marine ecosystem. Global Change Biology, 17(2), 1235-1249.

Watanabe, M., Suzuki, T., O'Ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T. & Sekiguchi, M. (2010) Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. Journal of Climate, 23(23), 6312-6335.

Wenger, S.J., Som, N.A., Dauwalter, D.C., Isaak, D.J., Neville, H.M., Luce, C.H., Dunham, J.B., Young, M.K., Fausch, K.D. & Rieman, B.E. (2013) Probabilistic accounting of uncertainty in forecasts of species distributions under climate change. Global change biology, 19(11), 3343-3354.

Wesenberg-Lund, E. (1950) The Polychæta of West Greenland: With Special Reference to the Fauna of Nordre Strømfjord, Kvane-, and Bredefjord. CA Reitzel.

Williams, A.B. (1984) Shrimps, lobsters, and crabs of the Atlantic coast of the eastern United States, Maine to Florida. Smithsonian Institution Press Washington, DC.

Williams, S.L., Davidson, I.C., Pasari, J.R., Ashton, G.V., Carlton, J.T., Crafton, R.E., Fontana, R.E., Grosholz, E.D., Miller, A.W. & Ruiz, G.M. (2013) Managing multiple vectors for marine invasions in an increasingly connected world. BioScience, 63812), 952-966.

Willis, K.J., Cook, E.J., Lozano-Fernandez, M. & Takeuchi, I. (2004) First record of the alien caprellid amphipod, *Caprella mutica*, for the UK. Journal of the Marine Biological Association of the UK, 84(05), 1027-1028.

Wisz, M.S., Broennimann, O., Grønkjær, P., Møller, P.R., Olsen, S.M., Swingedouw, D., Hedeholm, R.B., Nielsen, E.E., Guisan, A. & Pellissier, L. (2015) Arctic warming will promote Atlantic-Pacific fish interchange. Nature Climate Change, 5(3), 261-265.

Wisz, M.S., Pottier, J., Kissling, W.D., Pellissier, L., Lenoir, J., Damgaard, C.F., Dormann, C.F., Forchhammer, M.C., Grytnes, J.-A., Guisan, A., Heikkinen, R.K., Høye, T.T., Kühn, I., Luoto, M., Maiorano, L., Nilsson, M.-C., Normand, S., Öckinger, E., Schmidt, N.M., Termansen, M., Timmermann, A., Wardle, D.A., Aastrup, P. & Svenning, J.-C. (2013) The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. Biological Reviews, 88(1), 15-30.

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

Xu, J., Wickramarathne, T.L., Chawla, N.V., Grey, E.K., Steinhaeuser, K., Keller, R.P., Drake, J.M. & Lodge, D.M. (2014) Improving management of aquatic invasions by integrating shipping network, ecological, and environmental data: data mining for social good. In Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery and data mining (pp. 1699-1708). ACM.

Yoshioka, P.M. (1982) Role of Planktonic and Benthic Factors in the Population Dynamics of the Bryozoan *Membranipora Membranacea*. Ecology, 63, 457-468.

Zerebecki, R.A. & Sorte, C.J.B. (2011) Temperature tolerance and stress proteins as mechanisms of invasive species success. PLoS One, 6, e14806.