IDENTIFICATION AND RISK ASSESMENT OF POTENTIAL INVASIVE SPECIES IN GREENLAND WATERS

Scientific Report from DCE – Danish Centre for Environment and Energy No. 391 2020

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Data sheet

Series title and no.: Scientific Report from DCE – Danish Centre for Environment and Energy No. 391

Category: Scientific advisory report

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Publisher: Aarhus University, DCE – Danish Centre for Environment and Energy ©
URL: http://dce.au.dk/en

Year of publication: October 2020
Editing completed: October 2020

Referee: David Boertmann
Quality assurance, DCE: Kirsten Bang
Linguistic QA: Anne Mette Poulsen

Financial support: Danish Ministry of the Environment and Food as part of the environmental support program DANCEA.

Please cite as: Gustavson K., Wegeberg S., Christiansen T. & Geertz-Hansen O. 2020. Identification and risk assessment of potential invasive species in Greenland waters. Aarhus University, DCE – Danish Centre for Environment and Energy, 38 pp. Scientific Report No. 391 http://dce2.au.dk/pub/SR391.pdf

Abstract: Invasive species (invasive alien species) are of global conservation concern, and they may have strong, negative impacts on ecosystems, other species and valuable natural resources. So far, Arctic waters have experienced a relatively low number of biological introductions. However, observed increases in water temperatures resulting in reductions in sea ice forced by climate changes may increase shipping as well as the risk for introduction and establishment of non-native invasive species in Arctic waters. Based on a literature review and risk assessments, this report identifies species that potentially may become invasive in Greenland Arctic waters, and some of these may have potential high impacts on ecosystems and fisheries. As part of the project, Aarhus University has, in coordination with the Ministry of Environment and Food in Denmark and the Ministry of Nature and Environment in Greenland, contributed and provided input as needed to the implementation of the Arctic Invasive Alien Species Strategy and Action Plan 2017 (ARIAS), elaborated by the Arctic Council via the Conservation of Arctic Flora and Fauna (CAFF) and Protection of The Arctic Marine Environment (PAME) working groups. The report includes recommendations for the work in PAME and CAFF and for the development of a strategy to protect Greenland waters against non-native invasive species.

Keywords: Invasive, marine, Arctic, alien, Greenland waters, risk assessment, ARIAS, CAPP, PAME

Layout: Graphic Group, AU Silkeborg
Front page photo: Ole Geertz-Hansen

ISBN: 978-87-7156-514-0
ISSN (electronic): 2245-0203

Number of pages: 3833

Internet version: The report is available in electronic format (pdf) at http://dce2.au.dk/pub/SR391.pdf

Contents

Summary

Invasive species (invasive alien species) are of global conservation concern, and they may have strong, negative impacts on ecosystems other species and valuable natural resources. Well-known examples of marine invasive species intentionally introduced by man are the red king crab (*Paralithodes camtschaticus*) in the waters off northern Norway and the Kola Peninsula. Another example is the American comb jelly (*Mnemiopsis leidyi*) introduced by ballast water, which has had large ecological and economic impacts on the Caspian Sea and the Black Sea.

So far, Arctic waters have experienced a relatively low number of biological introductions. Their geographical remoteness, cold waters and presence of sea ice pose challenging conditions for both non-native organisms and the vessels that transport them, which presumably is the reason for the low rates of introduction and establishment. However, the currently observed increase in water temperatures resulting in reductions in sea ice forced by climate changes may increase shipping as well as the risk for introduction and establishment of non-native invasive species in artic waters.

Based on a literature review and risk assessments, this report identifies species that may potentially become invasive in Greenland Arctic waters, and some of these may have potential high impacts on ecosystems and fisheries. The report suggests that a warming of Arctic waters and a reduction of sea ice may increase the risk for invasion and establishment of non-native species in Greenland waters.

As part of this project, Aarhus University has, in coordination with the Ministry of Environment and Food in Denmark and the Ministry of Nature and Environment in Greenland, contributed and provided input as needed to the implementation of the Arctic Invasive Alien Species Strategy and Action Plan 2017 (ARIAS), elaborated by the Arctic Council via the Conservation of Arctic Flora and Fauna (CAFF) and Protection of The Arctic Marine Environment (PAME) working groups. This report is a national follow-up on actions defined in ARIAS to *improve the knowledge base in support of informed decision making.*

The report presents an assessment of species that pose a risk of becoming invasive in Greenland marine waters. The risk assessment includes information from governmental publications, national research reports, other scientific literature and risk assessments for other Arctic waters. The observed warming of Arctic waters is included in the assessment as a contributory factor towards increasing the risk for potential establishment of species introduced by shipping or transplantation to Greenland waters. The risk assessments include species that, based on the literature, are identified as potential threats to Greenland waters. The identified species represent different biology and reproductive strategies as well as different present distributions. As such, the identified species have different pathways and abilities to establish. Hence, it is to some extent possible to extrapolate between closely related species with comparable biology, for instance crabs such as red and brown king crabs. The list of potential invasive species is constantly evolving as new species distributions are observed and recorded. This report provides a basis for future invasive species risk assessments in Greenland waters.

The report includes recommendations for the work in PAME and CAFF and for developing a strategy for the protection of Greenland waters against non-native invasive species. A potential strategy is recommended to include: 1) Development of a regulatory system to control, avoid and manage introduction of non-native invasive species by ships (ballast water and biofouling); 2) identification of high risk shipping (ship types, shipping routes, sea areas etc.); 3) updating and maintenance of knowledge of species with risk of becoming invasive in Greenland; 4) development of monitoring systems for early detection / warning (e.g., interviews with fishermen and hunters and biological monitoring). The suggested actions can benefit from coordination and, where possible, collaboration with other countries in the Arctic.

The present report received financial support from the Danish Ministry of Environment and Food as part of the environmental support program 'Dancea'. The authors are solely responsible for all results and conclusions presented in the report, which do not necessarily reflect the position of the Danish Ministry of the Environment and Food or the Ministry of Nature and Environment in Greenland.

Sammenfatning

Spredning af invasive arter (invasive ikke hjemmehørende arter) er på verdensplan et stort problem. En invasiv art er indenfor biologien en art, der har spredt sig "kunstigt" til et nyt område, hvor den skader oprindelige arte. Kongekrabbe, også kaldet Kamchatkakrabbe, har spredt sig fra området ved Kola halvøen til norske farvande, hvor den har stor effekter på især bunddyr. Et andet eksempel er den Amerikanske ribbegople (populært kaldet Dræbergople), der har påført store skader og økonomiske tab for fiskeriet i Sortehavet.

Hidtil er der kun få eksempler på invasive arter i arktiske farvande. Imidlertid forventes det, at risikoen vil øges i takt med klimaændringerne. Organismer og herunder mulige invasive arter kan spredes over store geografiske afstande med skibe. Ballastvand fra skibe kan indeholde et stort antal organismer, og organismer kan frigives fra begroningen på skibes skrog. I takt med at klimaændringer vil reducere udbredelsen og tykkelse af havisen vil nye sejlruter i arktiske farvande blive anvendt og skibstrafikken vil generelt blive øget. Højere havtemperaturer øger tilsvarende risikoen for, at arter fra tempererede havområder kan etablere sig i de arktiske farvande.

Nærværende rapport er udarbejdet af DCE - Nationalt Center for Miljø og Energi under Aarhus Universitet i samarbejde Grønlands Naturinstitut. Rapporten er et bidrag til grundlaget for Miljø- og Fødevareministeriet i Danmark og Departementet for Forskning og Miljø i Grønlands Selvstyres implementering af Arktisk Råd's Strategi og handlingsplan om invasive arter i arktisk (ARIAS). ARIAS er initieret af arbejdsgrupperne CAFF (Conservation of Arctic Flora and Fauna) og PAME (Protection of the Arctic Marine Environment) under Arktisk Råd.

Risikovurderingen i rapporten er baseret på information fra statslige publikationer, nationale forskningsrapporter, anden videnskabelig litteratur og risikovurderinger udført for andre arktiske farvande. Klimaændringer, herunder opvarmning af arktiske farvande, er inddraget i vurderingen. I rapporten er desuden præsenteret en metode, der kan anvendes fremadrettet i forbindelse med risikovurdering af nye arter og for andre havområder.

I rapporten er udpeget en række arter, som vurderes at kunne være invasive i de grønlandske farvande. Flere arter af krabber vurderes at udgøre den største risiko. Desuden indeholder rapporten en række anbefalinger rettet mod arbejdet i CAFF, PAME og ARIAS, samt anbefalinger i forhold til beskyttelse af grønlandske farvande. Anbefalinger omhandler kontrol med skibe, der ankommer til grønlandske farvande, identifikation af skibstrafik med stor risiko og miljøovervågning.

Arbejdet med udarbejdelse af rapporten har modtaget økonomisk støtte fra det danske Miljø- og Fødevareministerium som en del af miljøstøtteprogrammet Dancea.

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1 Background

In the following, the term ”invasive species” is used for non-native species that are spread by human activities to new waters outside their natural range and which may pose a threat to resident species, their habitats and ecosystems functioning. The term "invasive species" corresponds to the term "Invasive Alien Species", i.a. used in the strategy and action plan of The Arctic Invasive Alien Species (ARIAS) under the two Arctic Council expert groups Conservation of Arctic Flora and Fauna (CAFF) and the Protection of the Arctic Marine Environment (PAME).

Marine invasive species are plants and animals (including their seeds, eggs, spores or other biological structures) that cause harm when they, intentionally or unintentionally, are introduced to a marine, estuarine or brackish ecosystem where they are not native. Not all introduced species survive in their new habitat, but those that thrive and reproduce have the potential to become invasive. There are certain characteristics that allow a species to flourish in the new environment and, as a result, negatively impact the ecosystem, local economy and, possibly, human health. Introduction of non-native marine species to new environments by ships or intentionally by man has been identified as a major threat to the world’s oceans, including the conservation of biodiversity and commercially exploited species, if they become invasive. Well-known examples of invasive species intentionally introduced by man are the red king crab (*Paralithodes camtschaticus*) in the waters of northern Norway and the Kola Peninsula and the Pacific oyster (*Crassostrea gigas*) in European waters. Invasive species transported with ballast water with large ecological and economic impacts include zebra mussel (*Dreissena polymorpha*) from the Caspian Sea / Black Sea to Europe and North America and the American comb jelly (*Mnemiopsis leidyi*) into the waters of Asia and Europe (see Box 1).

A multitude of marine species may have been unintentionally introduced, with shipping as the dominant vector, by either ballast water or biofouling on ship hulls, to new marine environments. In the new environment, they may survive to establish a reproductive population and may become invasive by out-competing native species and potentially multiplying into pest proportions.

According to the International Maritime Organization (IMO), the spread of invasive species is recognised as one of the greatest threats to the ecological and economic wellbeing of the seas (IMO 2016). It is estimated that thousands of species are daily transported in ballast water. In 2006, more than 1000 non-native species had been registered in European waters alone (Gollasch 2006).

The introduction of invasive species by shipping has intensified over the last few decades due to the expanded global trade and traffic volume. Since the volumes of seaborne trade continue to increase, the problem may not yet have reached its peak (IMO 2016).

Ballast water may be a vector for the introduction of invasive species as sea water transported by ships from one region may be discharged into the sea in another region of the world. Ballast water is pumped into ship tanks to maintain safe operating conditions throughout a voyage by compensating for a change in cargo load, shallow draft conditions or weather. Thus, while ballast water is essential for safe and efficient modern shipping operations, it may pose serious ecological, economic and health problems to recipient regions due to the multitude of marine organisms carried in ballast water. These include pathogens, bacteria, unicellular algae and small invertebrates, as well as different life stages (eggs, cysts and larvae) of various species.

In order to contain and minimise the risk of introducing invasive species by ballast water, the IMO Ballast Water Management Convention (in force by September 2017) requires all ships to implement a ballast water management plan. Ships and vessels that will discharge ballast water must use IMO approved systems for treatment of the ballast water to ensure that invasive non-native species are not transported or introduced to new waters. In 2020, Greenland will introduce similar rules for the treatment and discharge of ballast water. In 2020, the IMO Ballast Water Management Convention covers more than 90% of shipping worldwide.

Biofouling is also considered to be one of the main and significant vectors for bio-invasions (IMO) and is defined as the undesirable accumulation of marine organisms on submerged structures (especially ship hulls). Studies have shown that biofouling can be a significant vector for the transfer of invasive aquatic species. The IMO Biofouling Guidelines have been developed to control and manage biofouling in order to minimise the transfer of invasive benthic species.

The Arctic marine ecosystem is still relatively unaffected by non-native species compared with temperate and tropical regions because shipping activity has been low due to the extreme weather conditions and ice coverage. An example of this is that in European and Arctic waters, only 18 non-native species were registered in 2006, whereas the number for the Mediterranean was more than 300 (Gollasch 2006). However, the risk for introducing potential invasive species is expected to increase with the enhanced shipping traffic in the Arctic. Shipping through the Northeast/Northwest passages may bring North Pacific species to the North Atlantic and vice versa. Shipping in connection with the extraction of minerals, oil and gas in the Arctic may increase the risk of bringing southern species northwards. In addition, the warming of the oceans will increase the risk for transportation or introduction of invasive species to Arctic water where they may be able to establish and reproduce.

While there are currently few invasive non-native species in the Arctic, more are expected with the climate change and increased human activity in the area (CAFF 2013; Ware et al. 2014 and 2016; Bellard et al. 2016, Nordic Council of Ministers 2014). The Arctic Council has recognised that rapidly changing climatic conditions and a growing interest in resource extraction, settlement and tourism make the Arctic region particularly vulnerable to biological invasion (CAFF & PAME 2017, Bennett et al. 2015, Hall et al. 2010, Walther et al. 2009, McNeely 2001). The arrival of invasive non-native species will also impact people who depend upon the Arctic ecosystems for their livelihoods and well-being (CAFF 2013). Therefore, CAFF and PAME have developed the ARIAS Strategy and Action Plan to set forth the priority actions that the Arctic Council and its partners are encouraged to take. The overall aim is to protect the Arctic region from one of the significant emerging stressors: the adverse impacts of invasive non-native species.

The ARIAS Strategy and Action Plan identifies near-term priority actions that need to be taken in a cooperative manner. Through the plan the CAFF and PAME expert groups encourage each Arctic state to work collaboratively with its partners to integrate the actions from the ARIAS Strategy and Action Plan into national plans, as appropriate, and employ the priority actions as a means to advance relevant decisions made under the auspices of other multi-lateral fora and instruments.

The risk of introducing invasive species to the Arctic, including Greenland, from the outside follows the main shipping lanes (Figure 1).

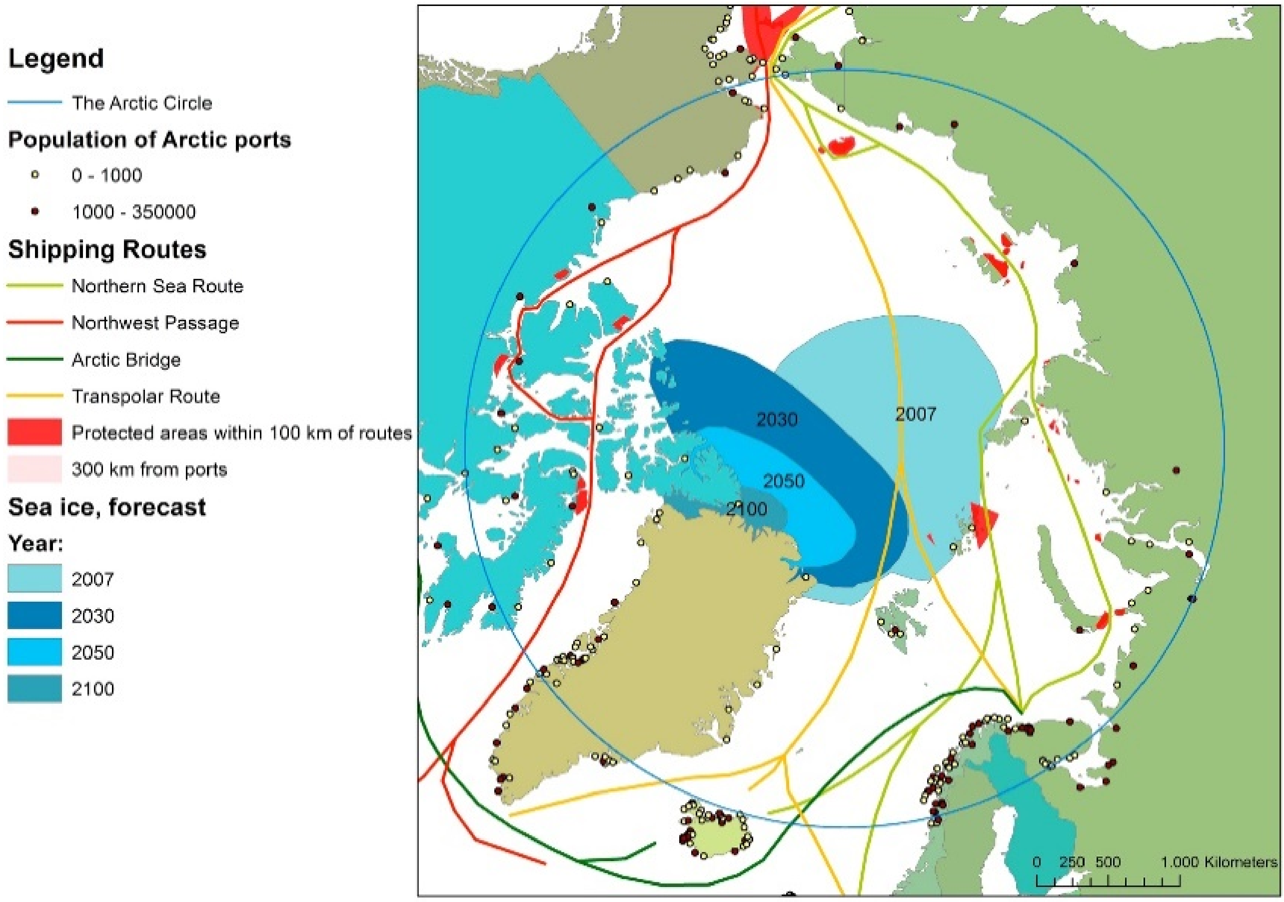


Figure 1. Future Arctic shipping routes mapped in relation to protected areas and distance from ports and a forecast of the reduction of sea ice in the Arctic (Eliasson et al. 2017).

The Arctic Shipping Status Reports by PAME track ship traffic in the Arctic based on data from PAME's Arctic Ship Traffic Database (ASTD). The first status report provides information on general Arctic shipping trends between 2013 and 2019 and shows the extent of the increase in much Arctic ship traffic. For example, during this six-year period, the number of ships entering the Arctic grew by 25%, and the distance sailed by ships in the Arctic increased by 75% (Arctic Shipping Status Reports, PAME 2020). The ship track for September 2019 demonstrates a relatively large ship traffic in Arctic waters (Figure 2).

The main objectives of the present project are to improve the knowledge base for the work in CAFF related to protection of the biodiversity in Arctic waters by:

- identifying potential invasive species into Greenland waters based on a literature review and databases on invasive species in Arctic waters and other relevant parts of the world.
- performing a risk assessment for Greenland waters as to introductory routes.

Further, participation in expert groups under CAFF / ARIAS is part of the project.

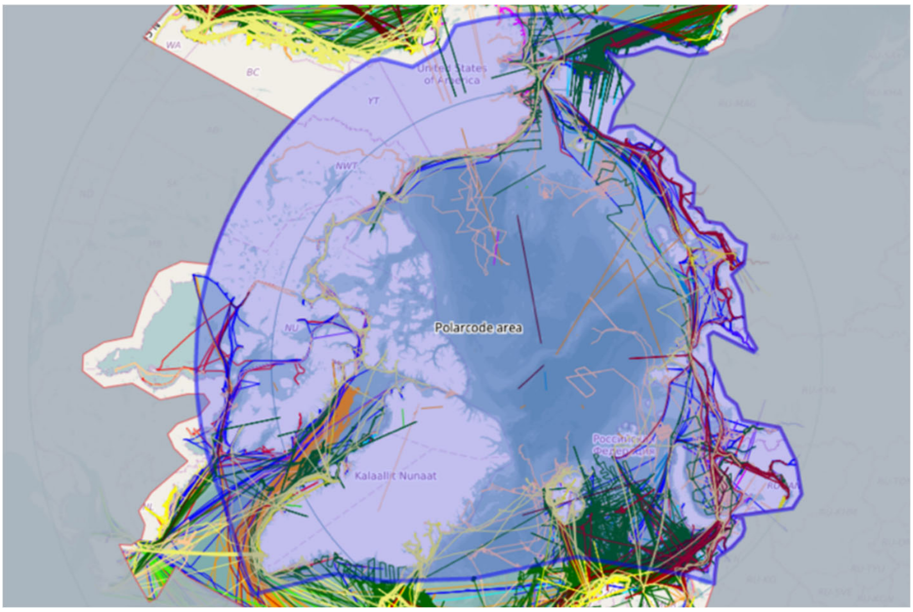


Figure 2. Ship tracks of all ships of all types in September 2019 (https://www.pame.is/projects/arctic-marine-shipping/arctic-shipping-status-reports/723-arctic-shipping-report-1-the-increase-in-arctic-shipping-2013-2019-pdf-version/file).

Box 1. Examples of aquatic invasive species. Non-native invasive species are plants and animals (including their seeds, eggs, spores or other biological structures) that cause harm when intentionally or unintentionally introduced into an ecosystem where they are not native. Not all introduced species survive in their new habitat, but those that thrive and reproduce are termed invasive if they negatively impact the existing ecosystem.

Red king crab (*Paralithodes camtschaticus*)

The red king crab was intentionally introduced into the Kola Bay area of the Russian Barents Sea for commercial fishery in the 1960s and has spread to Norwegian and Svalbard waters. The species is native to the northern Pacific/Bering Sea and is one of the largest crabs in the world (weighing up to 10 kg and having diameter of 1.5 m with extended legs). The red king crab feeds on benthos, such as polychaetes, mollusks and echinoderms, and has significant adverse effects on native biodiversity, both on their prey but also by reducing the availability of the prey to other native predators. It is a cold-adapted species with a temperature tolerance ranging from −1.8 to 12.8 °C, apparently with an optimum at 3.2 to 5.5 °C. However, reproduction and growth are highly temperature dependent and increase with higher end temperatures. Hence, the species has the potential to establish further in the Arctic and North Atlantic, (NBIC 2018).

North American comb jelly (*Mnemiopsis leidyi*)

One of the most damaging marine species invasions occurred in the early 1980s when the North American comb jelly, also called sea walnut, was introduced into the Black Sea through ballast water from the Atlantic coast of North America. The jellyfish had no native enemies and preyed on zooplankton, which caused a crash of the ecosystems. Within a few years it accounted for 90% of the total biomass in the Black Sea. It rapidly took hold and by 1989 an estimated 1 billion tonnes of the invasive species were consuming vast quantities of fish eggs and larvae, as well as the zooplankton that commercially important fish feed on. By 1992, the annual losses caused by decreases in commercial catches of marketable fish were estimated to be at least USD 240 million.(IMO 2016).

Box 2. Norwegian Biodiversity Information Centre (NBIC 2018) rates alien species in categories relative to potential ecological impact (severe impact, high impact, potentially high impact, low impact or no known risk). Ecological impact is defined as the product of invasion potential and ecological effect. https://www.biodiversity.no/alien-species-2018

Box 3. AquaMaps is an approach to generate model-based, large-scale predictions of currently known natural occurrences of marine species (https://www.aquamaps.org/main/home.php). The models are constructed from estimates of the environmental tolerance of a given species with respect to depth, salinity, temperature and primary productivity and its association with sea ice or coastal areas. The maps provide a colour-coded relative probability of a species to occur in a global grid of half-degree latitude/longitude cell dimensions. Predictions are generated by matching the habitat usage of species, termed environmental envelopes, with local environmental conditions to determine the relative suitability of specific geographical areas for a given species. AquaMaps 2100 displays the possible range of the natural distribution of a species by the year 2100 with respect to global climate change conditions described under the IPCC SRES A2 scenario. The AquaMaps 2100 model assumes no changes in species tolerances and habitat usage. Hence, the calculation of relative probabilities of occurrence in 2100 uses the same species environmental envelopes as that for the current native range. As the sea level rise is assumed to be negligible, the depth envelope is assumed to remain the same as today.

Box 4. Global Biodiversity Information Facility (https://www.gbif.org/) is an international network and research infrastructure funded by the world's governments and is aimed at providing anyone, anywhere, open access to data about all types of life on Earth. It should be noted that the Global Biodiversity Information Facility database (www.gbif.org/) does not contain information on the species distribution in Greenland and Russian waters.

2 Literature review of invasive species in Arctic waters – identified as potential invasive

Based on literature, a number of species have been identified as being potential invasive in Arctic waters. These are species whose requirements to environmental conditions match those in the Arctic, either now or at the rising temperatures related to the global climate change. The analysis included pelagic and benthic algae and fauna in seas of China, Japan, Canada, the US, Russia, the Antarctic seas and Scandinavia, with particular focus on Norway. The review includes introduction of species not just by sea currents but also by vectors such as ships.

2.1 Method for identification of potential invasive species in the Arctic

For the literature review, a bibliographic search was performed:

- in Google Scholar using relevant English keywords and their combinations, e.g., invasive, alien, species, marine, Arctic, Norway, Norw*, Canada, Canad*, Alaska, Alask*, Russia, Greenland.
- databases (global invasive species databases, World Register of Introduced Marine Species, The Alien Species List of Norway, CABI Invasive Species Compendium, and the California Non-native Estuarine and Marine Organisms / Cal-NEMO database).
- in reference lists of relevant articles / reports ('snow balling').

The obtained references were screened for relevance and all scientific articles, reports and memos considered relevant were included in the review.

The literature search resulted in 14 relevant publications (Table 1) in which four species were identified as invasive in Arctic waters (Table 2) and four as suspected alien, harmful and / or invasive (Table 3).

In addition, as shown in Table 1, the North American comb jelly (*Mnemiopsis leidyi*) was identified as a species with potential to be introduced to Arctic waters from the east coast of North America waters via natural and anthropogenic vectors.

Table 1. Selected scientific papers and reports obtained from a literature search identifying species as invasive or potentially invasive in specific nations/areas/regions.

Reference	Marine species in focus	Nation/area/region
NBIC (2018)	*Paralithodes camtschaticus*	Arctic
ARIAS (2017)	*Paralithodes camtschaticus*	Norway
Gederaas et al. (2012)	*Caprella mutica, Chionoecetes opilio, Crassostrea gigas, Ensis directus, Heterosiphonia japonica, Homarus americanus, Mnemiopsis leidyi, Paralithodes camtschaticus, Sargassum muticum, Acartia tonsa, Bonne-maissonia hamifera, Codium fragile, Styela clava*	Norway
Goldsmith (2016)	*Littorina littorea*, *Mya arenaria, Paralithodes camtschaticus, Ap-mhibalanus improvisus, Botrylloides violaceus, Carcinus maenas, Caprella mutica, Membranipora membranacea*	Canadian Arctic
Goldsmith & Archambault (2014)	*Streptospinigera niuqtuut, Paralithodes camtschaticus, Caprella mutica, Dumontia contorta*	Canadian Arctic
Havforskningsinstituttet (2014)	*Bonnemaissonia hamifera, Caprella mutica*	Narvik, Norway
Kourantidou et al. (2015)	*Paralithodes brevipes, Paralithodes camtschaticus, Chionoecetes opilio, Neodenticula seminae*	Arctic
Molnar et al. (2008)	*Acartia tonsa, Carcinus maenas, Dreissena polymorpha, Ectopleura crocea, Mya arenaria, Sphaeroma walkeri, Teredo navalis*	Arctic
Miljøstyrelsen (2017)	*Acartia tonsa*	Scandinavia
Rinde et al. (2017)	*Caprella mutica, Crassostrea gigas, Sargassum muticum*	Scandinavia
Spirinov & Zalota (2017)	*Paralithodes camtschaticus, Chionoecetes opilio*	Russia
Strandberg (2017)	*Gracilaria vermiculophylla, Sargassum muticum, Alexandrium minutum, A. tamarense, Chattonella verrulosa, Heterosigma akashiwo, Karenia mikimotoi, Pseudochatonella farcimen, Marenzellaria viridis, M. neglecta, Eriocheir sinensis, Cercopagis pengoi, Paralithodes camtschaticus, Mnemiopsis leidyi, Beroe spp., Neogobius melanostomus, Crassostrea gi-gas*	Denmark
Thomassen et al. (2017)	*Chionoecetes opilio,Cancer irrortus, Paralithodes camtschaticus, Acartia tonsa*	Svalbard
Thorarinsdottir et al. (2014)	*Fucus serratus, Cancer irroratus, Crangon, Platichthys flesus*	Iceland

Table 2. List of species identified as invasive in Arctic waters, however not in Greenland. Based on Kourantidou et al. (2015).

Popular name	Scientific name	Area
Red king crab	*Paralithodes camtschaticus*	Barents Sea, Norway
Brown king crab	*Paralithodes brevipes*	Alaska
Snow crab	*Chionoecetes opilio*	Barents Sea (native in western Greenland waters)
Diatom, planktonic	*Neodenticula seminae*	Labrador Sea, Irminger Sea

Table 3. List of species suspected to become invasive in Arctic waters based on Molnar et al. (2008), Kourantidou et al. (2015) and Miljøstyrelsen (2017).

Popular name	Scientific name	Area for introduction
Acartia copepod	*Acartia tonsa*	Scandinavia
European green crab	*Carcinus maenas*	Europe
Hydroid	*Ectopleura crocea*	Bering Sea
Soft-shell clam	*Mya arenaria*	Iceland
Naval shipworm	*Teredo navalis*	Atlantic Arctic

On a list of 25 species, identified as present or potentially invasive in Svalbard waters (see Appendix 1) (Norwegian Biodiversity Information Center (NBIC 2018), https://www.biodiversity.no/), the Norwegian king crab (*Lithodes maja*) is rated as a "potentially high impact" species, and the amphipod *Ischyrocerus commensalis*, living in symbiosis with and on the large crabs, as a "High Impact" species. Also on this list, the red king crab (*Paralithodes camtschaticus*) is rated as a "severe impact" species. The remaining 22 species on the Svalbard list are rated as "Low Impact" species.

3 Risk assessment in relation to Greenland waters

The potential risk of species listed in Table 2 and Table 3 of becoming invasive in Greenland is assessed below. In the risk assessment, we refer to the assessment made by the Norwegian Biodiversity Information Centre (NBIC 2018) regarding the Norwegian king crab (*Lithodes maja*) and the amphipod *Ischyrocerus commensalis*.

In the risk assessment of the species, the criteria described in the IMO Guidelines (IMO MEPC. 162(56)) are used. Categorisation of ecological risk is based on the classification used by the Norwegian Biodiversity Information Centre (Box 2). The possible future distribution of a species with respect to the predicted global climate change conditions is evaluated using distribution maps from the AquaMaps model (Box 3).

3.1 Red king crab (*Paralithodes camtschaticus*)

Present distribution/geographical areas

The red king crab is identified as an invasive non-native species in Arctic waters. In the 1960s, the red king crab was intentionally introduced into the Kola Bay area of the Russian Barents Sea for the purpose of commercial fishery. The species is native to the northern Pacific / Bering Sea and is one of the largest crabs in the world (up to 10 kg in weight and with a diameter of 1.5 m). Its occurrence records in the Global Biodiversity Information Facility Database (https://www.gbif.org/, Box 4) are shown in Figure 3. It should be noted that neither Greenland nor Russian data are included in this database.

Figure 3. Occurrence records of red king crab (*Paralithodes camtschaticus*). From https://www.gbif.org/.

Habitat range and potential distribution in the Arctic

The AquaMaps model predicts that environmental conditions may be suitable for red king crab in southeastern and southwestern Greenland waters in the near future (Figure 4). Model predictions indicate that the probability of establishment of the red king crab in Greenland waters will increase in the future.

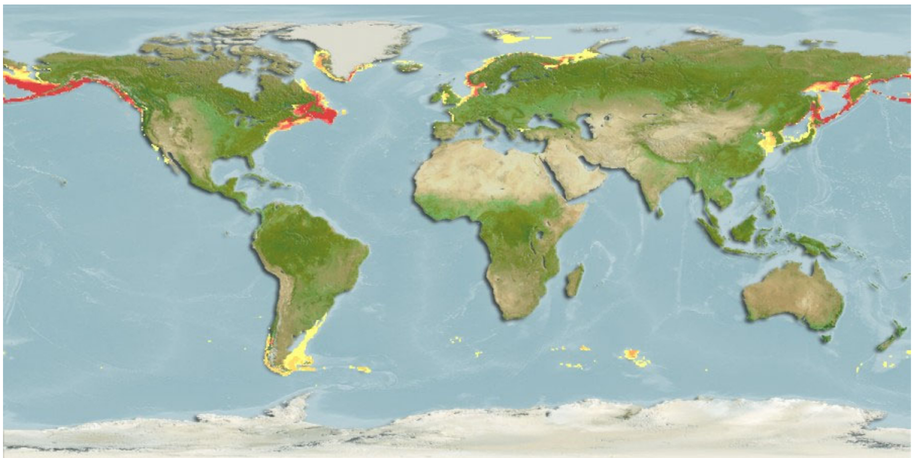


Figure 4. AquaMaps 2100-generated distribution maps for red king crab (*Paralithodes camtschaticus*) in year 2100 based on the IPCC A2 climate change emissions scenario. Distribution range colours indicate suitable habitats in both East and West Greenland in 2100. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.

The red king crab is a cold water species and can withstand temperatures from -1.6 up to 18 °C. The optimum temperature for the species is in the range 2-7 ºC, depending on life cycle stage (Sundet 2018, NBIC 2018).

Little is known of the salinity tolerance of the red king crab. In its most northern distribution range (Nome, Norton Sound in Alaska), it occurs in ice-covered shallow coastal water but is absent during the ice-free period. Bottom salinity and temperature were 34 ppt and –1.8ºC (CABI) during the ice-covered period and 22-24.5 ppt and 8.8-11ºC during the ice-free period (CABI). This suggests that salinity plays a role in the absence of the crab during ice-free periods. The red king crab is known to tolerate temperatures of –1.7 to +11ºC (CABI), varying with life history stage.

Potential dispersal propagules and vectors

The species is found from a few meters depth down to 500 m, depending on age, sex and season. The young crabs thrive best on rough gravel or rocky surfaces, while the adult individuals prefer sandy and mud bottoms. A female crab normally spawns between 100,000 and 400,000 eggs. After hatching, the king crab larva lives in the upper water layers where it can be transported over great distances by the ocean currents. The larvae pass through several pelagic stages during two months.

Potential impact of the invasive species

The Norwegian Biodiversity Information Centre (NBIC 2018) is responsible for regularly assessing the ecological impact of non-native species in Norway. In the latest assessment, the red king crab is rated as a “severe impact” species. The species has a high reproductive potential and a high dispersal rate. NBIC estimates that the species will invade coastal areas and fjords on the west coast of Svalbard within a few years.

Studies from the Varanger fjord in Norway also indicate that the red king crab by preying on benthic animals in the sediments contributes to a reduction in the quality of the sediments as removal of benthos reduces the transport of oxygen downwards in the seabed (NBIC 2018).

Adult red king crabs are opportunistic omnivores (CABI) that feed on the most abundant benthic organisms, and they may thus impact native biodiversity and exploit the commercial stock of fish. An assessment of the potential impact of the invader on commercial scallop (*Chlamys islandica*) beds showed that all size classes of crab preferred scallops (CABI). Research suggests that red king crabs are indirectly responsible for increased transmission of the blood parasite *Trypanosoma* to cod (*Gadus morhua*) by promoting an increase in the populations of a leech species that acts a vector for the parasites and which prefers to deposit its eggs on the crabs (CABI).

It has been documented that red king crab feed on fish eggs during their spring mass spawning (NBIC 2018). However, an investigation on king crab consumption of capelin (*Mallotus villosus*) eggs showed that the crabs only consumed 0.03% of the capelin egg spawning mass in the Russian economic zone (CABI), indicating that capelin may be resistant to this invasive crab species.

Risk in relation to Greenland waters

The AquaMaps model predicts that, in the near future, the changes in environmental conditions due to global warming may result in existence of suitable habitats for the red king crab in south-eastern and south-western Greenland waters. Research suggests that the lower salinity in, for instance, fjords may limit the distribution of the crab here (NBIC 2018).

After hatching, the red king crab larvae live in the upper water layers where they can be transported over great distances by the ocean currents (Figure 4), in ballast water as well as via biofouling on ship hulls.

In this context, special focus should be placed on ships entering Greenland waters from the Bering Sea, the Gulf of Alaska, the Norwegian Sea, the Barents Sea, the Sea of Okhotsk and waters near Japan and Korea.

Since the red king crab may have significant ecological effects on benthos and fish in Greenland waters, it is rated a ”severe impact” species. Added to this should be its potential impact on snow crabs, which has not yet been clarified.

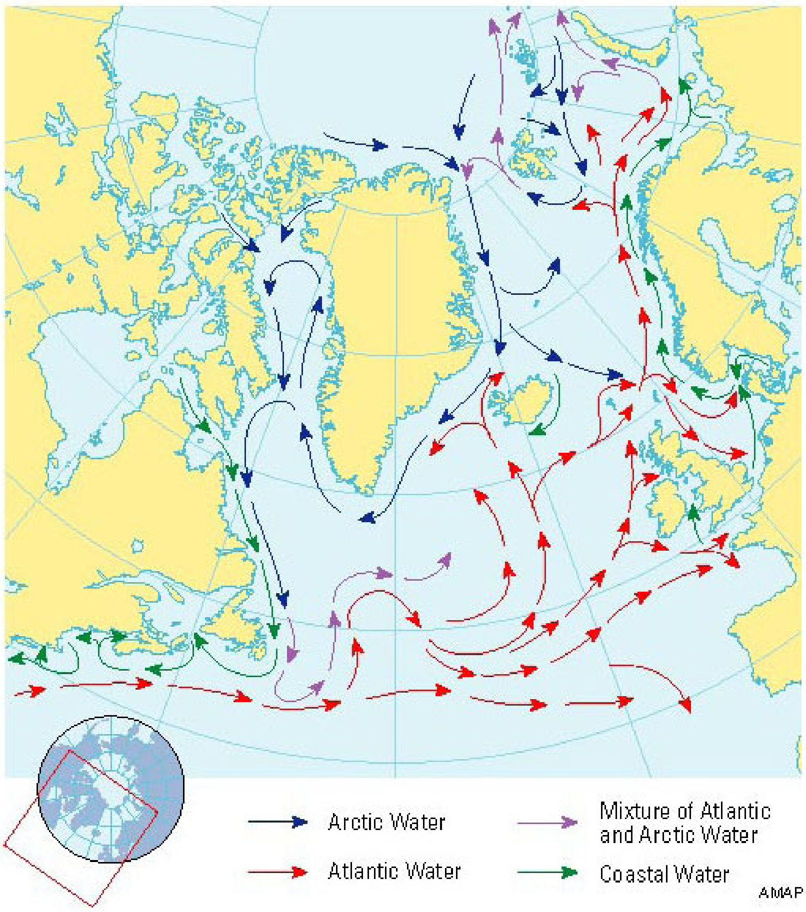


Figure 5. Ocean currents in the Polar Sea, the North Atlantic and around Greenland (AMAP).

3.2 Brown king crab (*Paralithodes brevipes*)

Present distribution/geographical areas

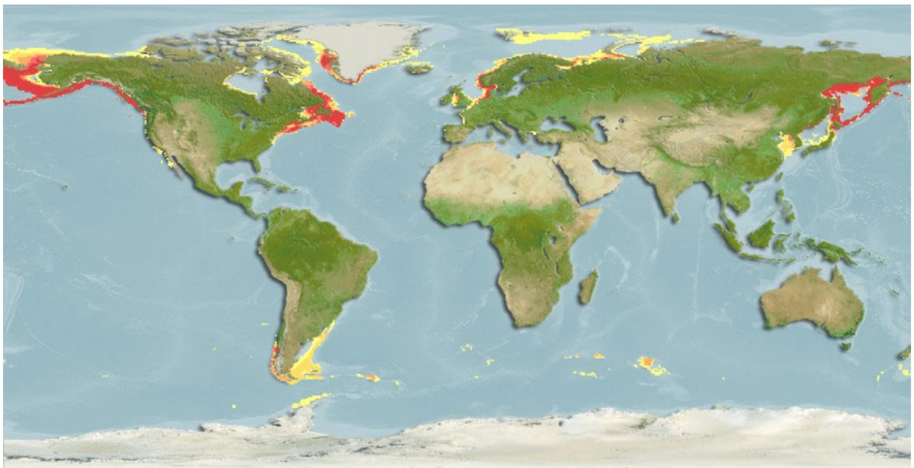
The brown king crab is found in the northwestern Pacific, the Okhotsk Sea, Japan and Russia, and thus covers temperate to Arctic ecosystems. Occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 6.

Figure 6. Occurrence records of brown king crab (*Paralithodes brevipes*). From https://www.gbif.org/.

Habitat range and potential distribution in the Arctic

The AquaMaps model predicts that environmental conditions may be suitable for the brown king crab in Greenland waters in the near future (Figure 7). The species may thus establish viable populations if introduced into Greenland waters.

Figure 7. AquaMaps 2100-generated distribution maps for brown king crab (*Paralithodes brevipes*) in year 2100 based on the IPCC A2 climate change emissions scenario. Distribution range colours indicate that habitats in both East and West Greenland may become suitable for the brown king crab in 2100. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.



The brown king crab has a depth range of 0-280 m with a preferred optimal temperature around 6°C.

Potential dispersal of propagules and vectors

The high reproduction potential and resultant risk for dispersal are assessed similar to those of the red king crab (see above).

Potential impact of the invasive species

The impact of brown king crab is assessed as being similar to that of the red king crab. However, as the two king crab species may inhabit the same (deep sea) habitats, interspecific competition may have a regulatory effect on both populations, or cumulative effects may occur.

Risk in relation to Greenland waters

Overall, it is assessed that there is significant risk that brown king crab will be able to reproduce and spread in Greenland waters. Data in the Global Biodiversity Information Facility database (GBIF) indicate that its present distribution is limited to the Okhotsk Sea and the West Bering Sea. However, it should be noted that the distribution of species in the GBIF database and on maps do not include data from Russian and Greenland waters. For Arctic waters, the GBIF database only contains data from the US, Canada, Japan, Norway, Sweden, Finland and Iceland.

As the distance from the present distribution of the crab species to Greenland is (still) long, a potential spreading into Greenland waters may be with a ship vector (ballast water or biofouling on the hull) as eggs or larvae.

Since the brown king crab may have a significant effect on the benthos and fish in Greenland waters, it is rated as a "potentially high impact" species.

3.3 Snow crab (*Chionoecetes opilio*)

Present distribution/geographical areas

The natural distribution of snow crab (*Chionoecetes opilio*) is on the west and east coasts of North America and from the northern parts of Japan to the Bering Sea and the west coast of Greenland. Commercial fishing takes place on the west coast of Greenland. Snow crab is included in this report in relation to possible invasion of eastern Greenland waters. For Svalbard, NBIC rates snow crab in the "potentially high impact" category. Its occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 8.

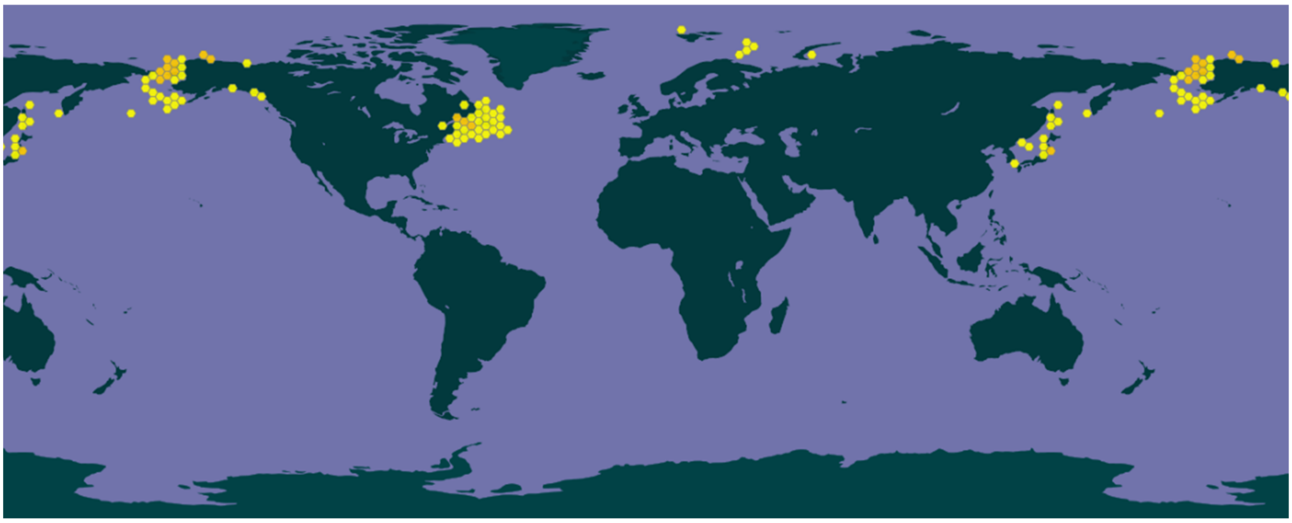


Figure 8. Occurrence records of snow crab (*Chionoecetes opilio*).

From https://www.gbif.org/. It should be noted that Russia and Greenland are not part of the Global Biodiversity Information Facility network, and the current occurrence of snow crabs in Greenland is thus not registered on the map. For Arctic waters, the GBIF database contains only data from member countries including the US, Canada, Japan, Norway, Sweden, Finland and Iceland.

The present occurrence of snow crab in the Barents Sea is attributed to transfer of larvae in ballast water (NBIC 2018). At present, the snow crab has a large population in the Russian part of the Barents Sea. In the eastern parts of the Norwegian zone in the Barents Sea, snow crab catches have increased steadily since 2004, and recently snow crab was observed for the first time in the Raudfjord on Svalbard (NBIC 2018).

Habitat range and potential distribution in the Arctic

The AquaMaps model predicts that environmental conditions may be suitable for northward propagation of snow crab in the near future (Figure 9).

The snow crab normally lives in water bodies with temperatures lower than 3 °C.

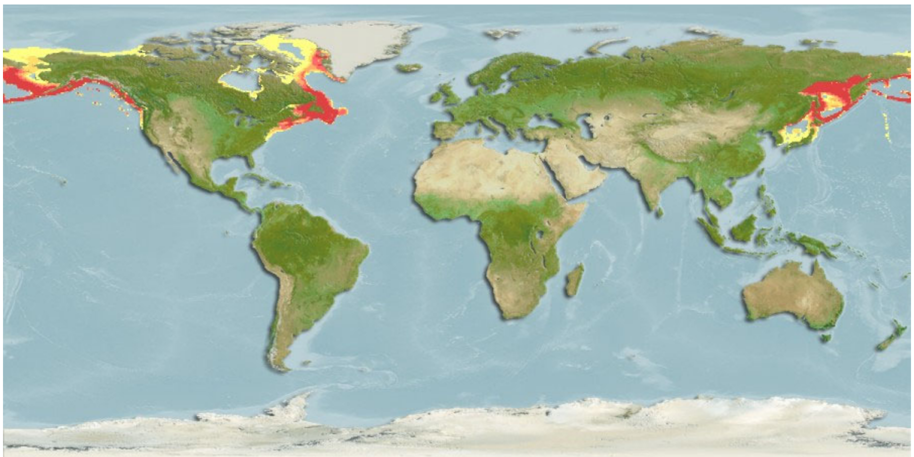


Figure 9. AquaMaps 2100-generated distribution maps for snow crab (*Chionoecetes opilio*) in year 2100 based on the IPCC A2 climate change emissions scenario. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.

Potential dispersal propagules and vectors

Small crabs and female crabs usually live in shallower areas than the large male crabs, the actual depths varying widely from area to area. The snow crab is usually found on a soft bottom but may sometimes also reside in typical hard bottom areas (NBIC 2018). After hatching, the larvae live in the upper water layers where they can be transported over great distances by the ocean currents. The larvae pass through several pelagic stages for about two months.

The snow crab spawns fewer eggs per female than the king crab, but unlike the king crab, the larvae do not depend on settling in shallow areas and therefore have a larger settling area.

Studies conducted on the eastern coast of Canada show that the snow crab and its propagules migrate over long distances and at varying depths depending on life stages (NBIC 2018).

Potential impact of the invasive species

In the latest assessment of snow crab by the Norwegian Biodiversity Information Centre (NBIC 2018), the species was rated as a ”potentially high impact” species due to its high reproductive potential and high dispersal rate.

The species has recently been observed for the first time at Svalbard and is assessed as potentially having a significant effect on the seabed fauna (NBIC 2018). However, it should be emphasised that the current knowledge of snow crab effects on benthos is limited and that the assessment primarily is based on data on red king crab. However, the two crab species have fairly similar diets, thus allowing comparison.

Risk in relation to Greenland waters

Snow crab has recently been observed waters around Svalbard and northern Norway, and it cannot be ruled out that it will be able to reach and establish also in East Greenland waters.

After hatching, the larva lives in the upper water layers where it can be transported over great distances by the ocean currents. However, the present distribution of snow crab in the Barents Sea is attributed to transfer of larvae in ballast water. For Greenland, it is assessed that eggs or larvae may be transported to East Greenland waters in ballast water and biofouling on ship hulls and by ocean currents.

3.4 The marine diatom (*Neodenticula seminae*)

Present distribution/geographical areas

The geographical distribution of the temperate planktonic diatom *Neodenticula seminae* is in the northern North Pacific and the Bering Sea, but the species has been introduced to the North Atlantic, the Labrador Sea, Gulf of St. Lawrence and the northern Nordic seas (Miettinen 2018). Its occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 10.

Figure 10. Occurrence records of the diatom species *Neodenticula seminae*. From https://www.gbif.org/.

Habitat range and potential distribution in the Arctic

The discovery of the North Pacific diatom *Neodenticula seminae* in the Labrador Sea in 1999 by Reid et al. (2007) indicates that the reduction of Arctic sea ice has influenced water current patterns. The authors discuss ballast water as a possible vector for the diatom but conclude that given the small number of ships and volumes of ballast water moving between the two regions in the late 1990s, ballast water was an unlikely vector.

Potential dispersal routes or vectors

Neodenticula seminae may spread with ballast water as well by sea currents. Reduced ice and increased sea temperature may increase the probability for this diatom to propagate northwards.

Potential impact of the invasive species

The potential impact of the introduction of *N. seminae* may be changes in the plankton community through competition with the endemic phytoplankton species.

Risk in relation to Greenland waters

Model estimation indicates a high invasion potential of *N. seminae* in Greenland waters. However, since its ecological effects are low, small or insignificant, it is rated as a "No known impact" planktonic diatom species.

3.5 Acartia copepod (*Acartia tonsa*)

Present distribution/geographical areas

The copepod *Acartia tonsa* originates from North America and the Pacific Ocean but was discovered in the North Sea in 1916 and in Scandinavia (Sweden) in 1934. Now it is distributed throughout the Skagerrak, the Kattegat and the Baltic Sea and occurs as well in estuaries in Britain, along the coasts of Europe and at both the Atlantic and Pacific coasts of North America. Worldwide, the species inhabits subtropical, tropical and other warm waters. Its occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 11.

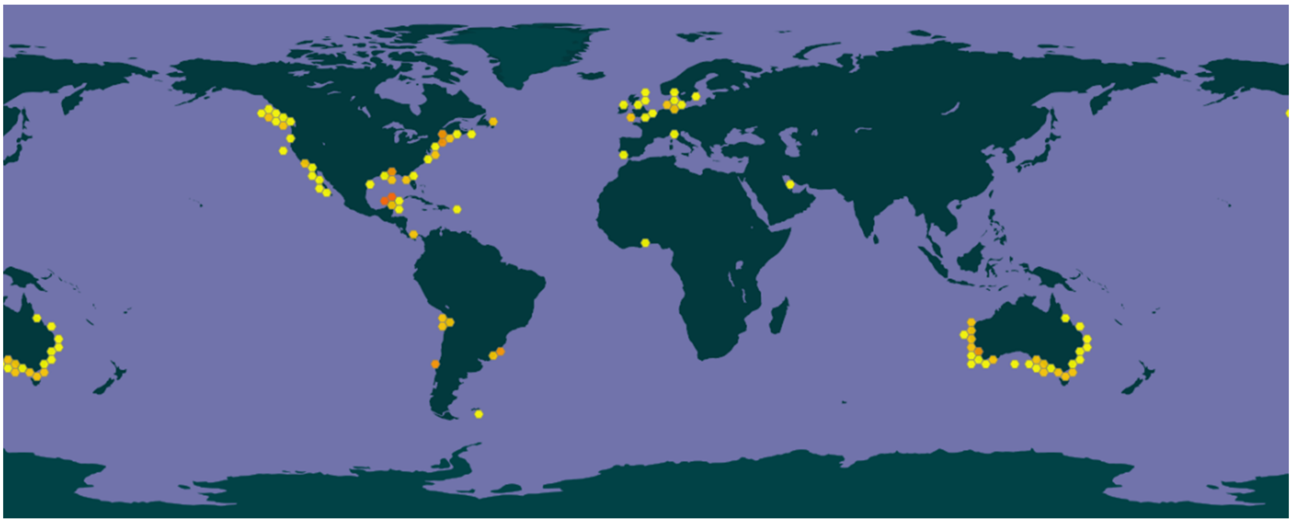


Figure 11. Occurrence records of *Acartia tonsa*. From https://www.gbif.org/.

Habitat range and potential distribution in the Arctic

Arcatia tonsa requires water temperature of minimum 10°C for successful reproduction, and the species seems to be restricted to estuarine habitats with salinities within the range of 15 to 22 psu. Adaptation to even lower salinities may occur, and the species is found in the Caspian Sea where the salinity range is 7–8 psu.

Isolated pockets of warmer, brackish waters may occur in the Arctic and act as attractive habitats to *A. tonsa*. As the species may be highly adapted to salinity and temperature, this may be a barrier for the species to overcome if it is introduced. However, the strong seasonality of light, leading to strong seasonality in food availability, calls for strategies for the copepod to survive long periods with no feeding in the Arctic.

Potential dispersal routes or vectors

The *A. tonsa* copepod may spread as adults as well as eggs. It may produce resistant diapause eggs induced by, for instance, food shortage. Successful reproduction requires a minimum temperature of 10°C, and the species goes through a life cycle with six larvae stages. Possible vectors are ballast water and sea currents. In addition, reduced ice coverage and increased sea temperatures caused by the climate changes may enhance the species' probability to propagate northwards.

Risk in relation to Greenland waters

Apparently, no adverse effects have been observed after the introduction of *A. tonsa* to the Caspian Sea. However, the already present often lipid rich *Calanus* copepods may be better fitted to the strong seasonality in food availability in the Arctic waters.

Reduced ice cover and increased sea temperatures may increase the probability of *A. tonsa* to propagate northwards and develop in pockets of warmer waters. However, since the species is not adapted to the strong seasonality in food availability in Greenland waters, it is assessed that the Arctic *Calanus* species will outperform *A. tonsa*. Accordingly, in relation to Greenland waters, *A. tonsa* is rated as a "Low impact" species.

3.6 The hydroid (*Ectopleura crocea*)

Ectopleura crocea is a hydrozoan, which lacks a medusa stage. Its colonies grow from branching stolons in tangled masses up to 100-120 mm in height and consist of up to several hundred unbranched stems, with one hydranth per stalk. (Cal-NEMO, https://invasions.si.edu/nemesis/calnemo/SpeciesSummary.jsp?TSN=-33).

Present distribution/geographical areas

The natural geographical distribution of this hydrozoan species ranges from the east and west coast of North America to Alaska (Cal-NEMO). However, *E. crocea* has been introduced to Australia, New Zealand, Europe, the Mediterranean, the Azores, Madeira and South Africa. Its occurrence records in the Global Biodiversity Information Facility Database (GBIF) are shown in Figure 12.

Figure 12. Occurrence records of the hydroid *Ectopleura crocea*. From https://www.gbif.org/.

E- crocea is generally found in harbours and polluted waters as part of fouling communities and inhabits substrates such as rocks, shells, concrete, pilings and ship hulls.

Potential distribution in the Arctic

The AquaMaps model predicts that environmental conditions in the Arctic may be suitable for the establishment of *Ectopleura crocea* (Figure 13 in the near future). The distribution range colours indicate that habitats in both South-East and South West Greenland may be suitable for the hydroid species in 2100.

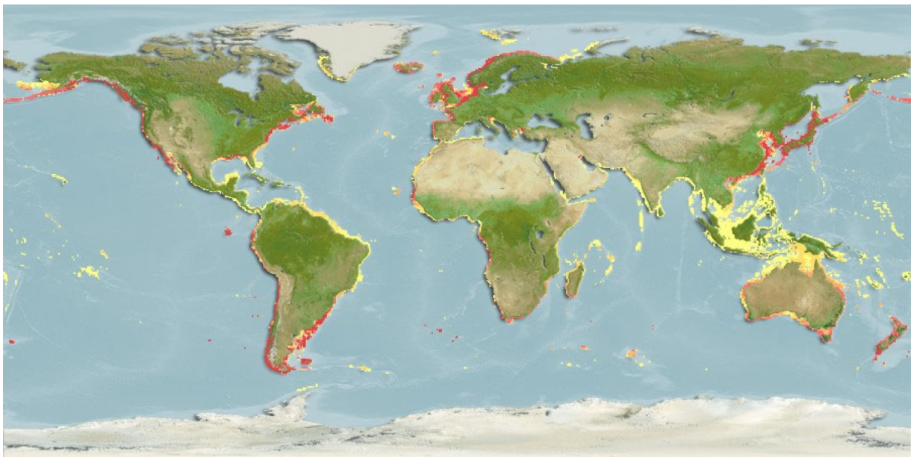


Figure 13. AquaMaps 2100-generated distribution maps for the hydroid *Ectopleura crocea* in year 2100 based on the IPCC A2 climate change emissions scenario. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.

Dispersal propagules and vectors

E. crocea lacks the planktonic medusa stage, which could have been a vector for spreading. Therefore, the species may spread as adult polyp stages already established in fouling communities on, for instance, ship hulls or as larvae. The larvae are planktonic and their production (few / many) may vary regionally.

Potential impact of the invasive species

E. crocea occurs on mussel shells and around mussel beds, and it is a potential competitor with mussels and a possible predator on their larvae (Cal-NEMO). As a result of its introduction, fouling of marine cultivation systems occurs with potential adverse effects on the growth and condition of the cultivated organisms.

Risk in relation to Greenland waters

The primary vector for introduction of the hydroid *Ectopleura crocea* to Greenland water is biofouling on ship hulls and in ballast water.

It is assessed that the ecological effect of the species in Greenland is small due to the absence of sea-based cultivation systems. Therefore, at present, , the hydroid is rated as a “Low impact” species.

3.7 Soft-shell clam (*Mya arenaria*)

Present distribution/geographical areas

These mussels are suspension feeders and live buried in tidal mud or sand flats. *Mya arenaria* originated in the Pacific Ocean and extended its range in geological time into the Atlantic, including European waters, but became extinct, leaving only a population in the Northwest Atlantic. Its present geographical distribution in the Arctic is along the Pacific coast of North America, including Alaska and Canada (Cal-NEMO). It also occurs in Scandinavian waters as well as in the White Sea (Cal-NEMO). Its occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 14.

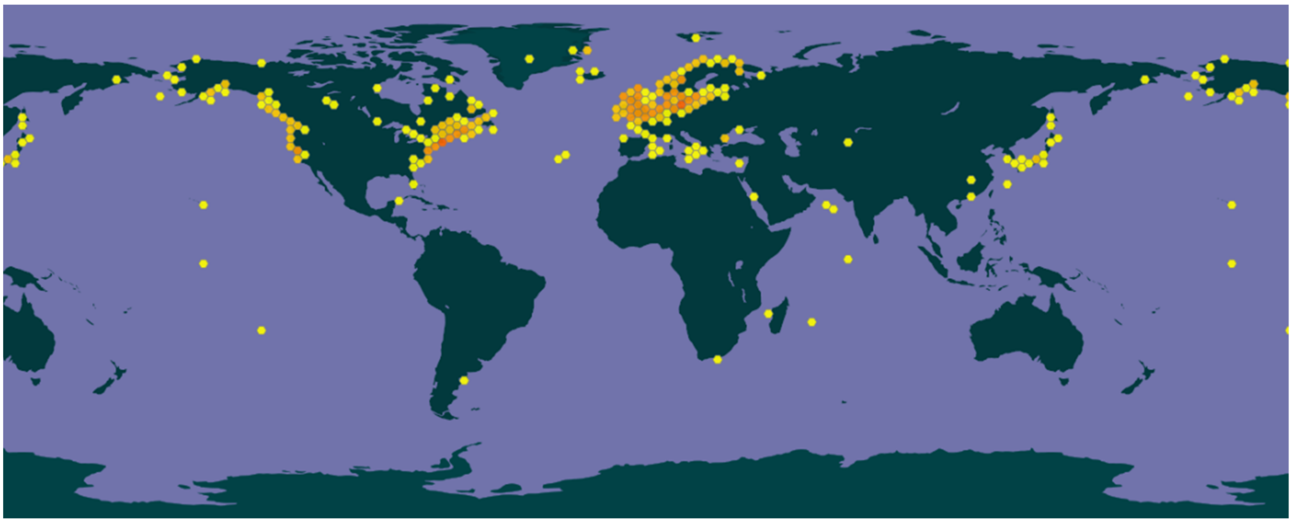


Figure 14. Occurrence records of soft-shell clam (*Mya arenaria*). From https://www.gbif.org/.

Habitat range and potential distribution in the Arctic

The AquaMaps model predicts that the environment environmental conditions in the Arctic may be suitable for the soft-shell clam in the near future (Figure 15). The distribution range colors indicate potentially suitable habitats for the bivalve in both South and West Greenland waters in 2100.

M. arenaria is usually tolerant of low salinities and can be acclimated to feed at 3 PSU (Cal-NEMO). Feeding rates are influenced by temperature, salinity and food quality. Filtration and assimilation may drop to very low levels below 3ºC. This bivalve species is able to feed in water with considerable quantities of suspended silt and are able to sort cells for silt particles before ingestion (Cal-NEMO).

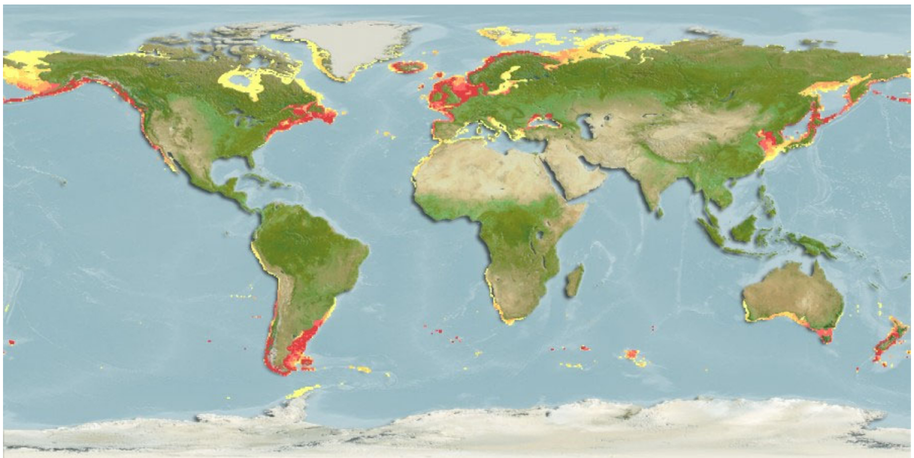


Figure 15. AquaMaps 2100-generated distribution maps for soft-shell clam (*Mya arenaria*) in year 2100 based on the IPCC A2 climate change emissions scenario. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.

Potential dispersal propagules and vectors

The reported fecundity of soft-shell clam ranges from about 100,000 to 3 million eggs. Fertilised eggs develop into pelagic larvae. After 12-30 days the larvae start settling on the seabed.

Only eggs and larvae may act as propagules for dispersal as adults are highly immobile. The eggs and larval stages can be transported in the ballasts of ships and as biofouling on ship hulls. *M. arenaria* is presumed introduced to the west coast of the United States via ship ballast water (.Cal-NEMO). Another suggestion is that *M. arenaria* was un-intentionally introduced to US waters during transportation of stocks of American oyster (*Crassostrea virginica*) (Cal-NEMO). NOBANIS (undated) states that *M. arenaria* was introduced to Estonia by hull fouling (ISSG).

Potential impact of the invasive species

If their abundance is high, the species may become dominant in their habitat and compete for food and space with other native bivalves and hence change the composition of the benthic community. During periods of exceptional abundance, *M. arenaria* may have effects throughout the food web – on phytoplankton abundance and, in turn, zooplankton, mysids and fish recruitment (CAL-NEMO).

Risk in relation to Greenland waters

The primary vector for introduction of soft-shell clam to Greenland waters is considered to be biofouling on hulls and ballast water. The species may affect the native bivalves and change the composition of the benthic community. However, as *M. arenaria* requires relatively high temperatures for spawning, it is categorised as a “Low impact” species.

3.8 Naval shipworm (*Teredo navalis*)

Present distribution/geographical areas:

The bivalve *Teredo navalis* has a brownish elongated worm-like body whose anterior part is covered by a small calcareous tube shell acting as a wood-boring instrument. *T. navalis* has been found worldwide and is a well-established species in European, North American and northwestern Pacific coastal areas. However, its origin is still to be determined. Its occurrence records in the Global Biodiversity Information Facility Database are shown in Figure 16.

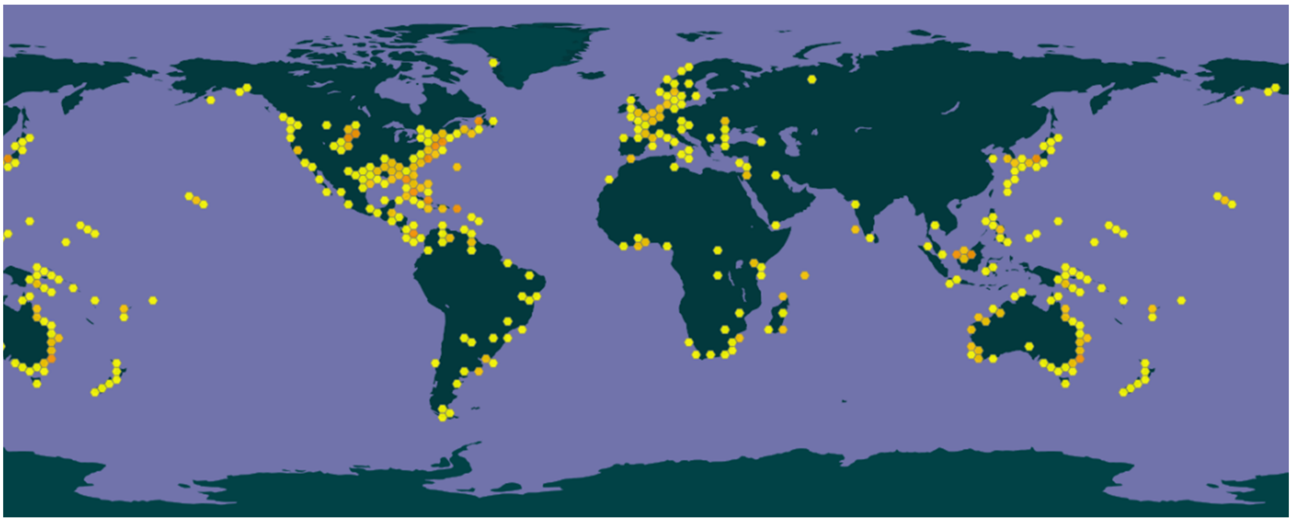


Figure 16. Occurrence records of naval shipworm (*Teredo navalis*). From https://www.gbif.org/.

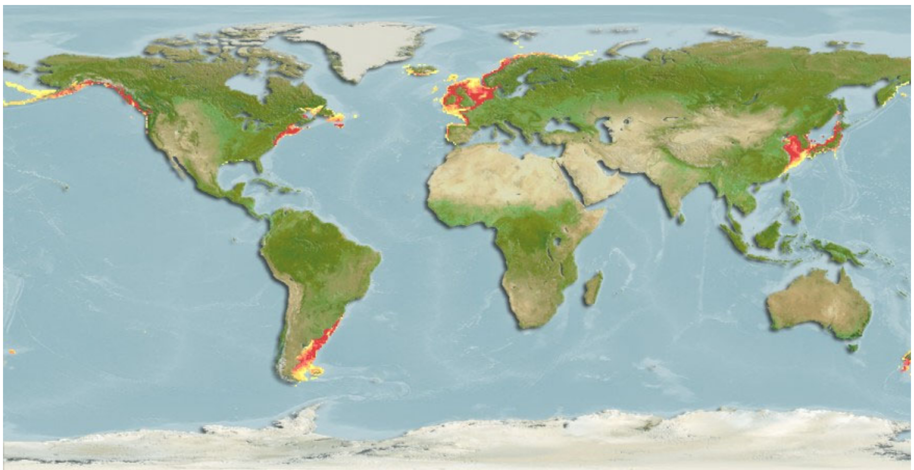
Habitat range and potential distribution in the Arctic

Naval shipworm is found in brackish and oceanic waters and tolerates (survives) temperatures from 1 to 30 °C, although its growth and reproduction are restricted to the temperature range 11-25 °C.

The species is both eurythermic and euryhaline and it thus withstands a wide range of temperatures and salinities. Its larviparous life strategy (long larval life) is effective for surviving in patchy ephemeral habitats, such as wood. Due to its boring activity, the species quickly destroys wooden structures submerged in water at depths of 0 to 20 m, and it therefore poses a great hazard to wooden maritime structures in coastal areas and causes millions of dollars of damage per year. The recent range expansion of *T. navalis* into the Baltic Sea suggests that the species adapts to lower salinity conditions (CABI).

The northernmost distribution of the species includes coastal water of Norway, Labrador, Newfoundland and southern Alaska. The species has most likely been spread to all seas with driftwood and with wooden ships from the Middle Ages and up to modern times. In Norway, *T. navalis* is listed as a 'No known risk' species (NBIC 2018).

Figure 17. AquaMaps 2100-generated potential distribution maps for naval shipworm (*Teredo navalis*) in year 2100 based on the IPCC A2 climate change emissions scenario. From www.aquamaps.org, August 2016 version. Web accessed 7 September 2018.



The AquaMaps model predicts where environmental conditions may be suitable for naval shipworm in the near future, and the distribution range colours indicate that Greenland waters may not be suitable for the naval shipworm in 2100 (Figure 17).

Dispersal propagules and vectors

The pelagic larvae may be transferred by sea currents and in ballast water. Adults may be spread in drift wood and wooden boat hulls.

Potential impact of the invasive species

Teredo navalis is called a shipworm because it resembles a worm, but in fact it has a small shell with two valves specialised at boring in wood. It tunnels into underwater piers and pilings and is a major cause of damage to and destruction of submarine timber structures and wooden boat hulls.

Risk in relation to Greenland waters

Pelagic larvae of the naval shipworm may be introduced by ballast water and adults by drifting wood. However, since the AquaMap model indicates that the environmental conditions in Greenland waters will not facilitate establishment of the naval shipworm, it is categorised as a “Low impact” species.

3.9 New potential invasive species

It should be noted that the performed risk assessments concern species that, based on the literature, are presently identified to potentially pose a high risk to Greenland waters. The selected species represent different biology and reproductive strategies as well as different distributions. Hence, it is – to some extent – possible to extrapolate between closely related species with comparable biology, for instance crabs such as red and brown king crab. The list of potential invasive species is constantly evolving as new species are observed and recorded. An example is the observed occurrence of pink salmon (*Oncorhynchus gorbuscha*) in Greenland waters in 2019. Based on information from social media, the Greenland Institute of Natural Resources has collected data on pink salmon, reporting observations of eighty-four individuals at 22 locations across Greenland (Nielsen et al. 2020). The increased abundance of pink salmon in Atlantic parts of the Arctic is attributed to increasing sea temperatures . At this stage, it is unknown if pink salmon are able to reproduce in Greenland waters and their potential invasion risk can, therefore, not be assessed. Pink salmon has periodically been introduced from the Pacific coast of North America to rivers of the White Sea and Barents Sea basins in Russia since 1956 but has not established self-sustained populations. In Norway, however, self-sustaining populations have been observed.

4 Conclusion and recommendations

4.1 Conclusion

The Arctic marine ecosystem is still relatively unaffected by non-native invasive species compared with temperate, subtropical and tropical regions due to the generally low shipping activity at these northern latitudes. Accordingly, in 2006, only 18 non-native species were registered in European and Arctic waters as opposed to more than 300 in the Mediterranean (Gollasch 2006). However, the risk for introduction of potential invasive species is expected to increase in step with an increase in shipping in the Arctic (Holbeck & Petersen 2018). Shipping through the Northeast / Northwest passages may bring North Pacific species to the North Atlantic and vice versa. Shipping in connection with the extraction of minerals and oil in the Arctic may augment the risk of bringing southern species northwards. Using a shipping vector-based approach (global port connectedness to the Svalbard archipelago, Norway) combined with the changing environmental match of seawater temperature and salinity under the RCP8.5 emissions scenario (IPCC 2013), and qualitative estimates of propagule pressure, Ware et al. (2014 and 2016) estimated the risk for invasions to Svalbard. Their modelling suggested that in the second half of the 21st century, Svalbard will become increasingly vulnerable to invasion as a function of climate change and increased propagule pressure from ships.

A multitude of marine species, introduced by discharge of ballast water or on ship hulls, transplanted by man or released from aquaculture, have in many other waters established reproductive populations in the host environment, thus becoming invasive, out-competing native species and multiplying into pest proportions.

On a global scale, the problem of invasive species carried by ships has intensified over the last few decades due to the expanding trade and traffic volume and, since the volumes of seaborne trade generally continue to increase, the problem may not yet have reached its peak.

Results from model simulations indicate that the warming of Arctic waters and reduction of sea ice will increase the risk for the establishment of new non-native species in Greenland waters.

Based on a literature review, a number of potential invasive species in Arctic waters have been identified. In this project, risk assessments with respect to Greenland waters have been carried out for selected species, and they. suggest that there is risk of species invasion to Greenland waters.

The risk assessments indicate a high invasion risk of various species of crabs. Pelagic crab larvae and eggs can be dispersed with ocean currents and ballast water and by biofouling on ship hulls. Adult crabs can migrate over large distances into new areas. A number of studies indicate that crab invasion can have major effects on biodiversity in general as well as on benthos community structure and fish populations. In addition, crabs may have parasites that can spread to fish. The Norwegian Biodiversity Information Centre (NBIC 2018) rated the crab species in the three categories “severe impact”, “high impact” and “potentially high impact”.

The primary vector for introduction to Greenland waters is considered to be biofouling on ship hulls and in ballast water as is assessed in this report for the bivalve *Mya arenaria*. *M. arenaria* may affect native bivalves and change the composition of the benthic community. However, since it requires relatively high temperatures for spawning, it is categorised as a "Low impact" species.

Model simulation estimation indicates a potential high risk of invasion of the planktonic diatom algae species *Neodenticula seminae* into Greenland waters. However, since its ecological effects are assessed as low, small or insignificant, it is rated as a "No known impact" species.

Reduced ice and increased sea temperatures may enhance the probability for northwards propagation and development of temperate species in pockets of warm water. However, the temperate copepod species *Acartia tonsa* is assessed not to be able to adapt to the strong seasonality in food availability in Greenland waters, implying that species of the Arctic copepod *Calanus* will be able to outcompete *A. tonsa*. In the assessment, *A. tonsa* is rated as a "Low impact" species.

The primary vector for introduction of the hydroid *Ectopleura crocea* to Greenland waters is considered to be biofouling on hulls and by ballast water. In the assessment, its ecological effects are considered to be small and with respect to Greenland waters, it is rated as a "Low impact" species.

Pelagic larvae of naval shipworm may be introduced by ballast water and adults by drifting wood. Since the AquaMap model indicates that the environmental conditions in Greenland water will not accommodate the requirements of the naval shipworm, it is categorised as a "Low impact" species.

In conclusion, it is generally recommended that reviews of species potentially posing an invasion threat to Greenland are performed regularly. Species statuses are dynamic and a species may change from being assessed as non-native species to invasive. In addition, secondary spread of invasive species could be a threat to Greenland waters. The fucoid macroalgae *Fucus serratus* might an example of this as in Nova Scotia / An example of this is the secondary spread of the fucoid macroalgae *Fucus serratus* in Nova Scotia (Johnson et al. 2012).

4.2 Recommendations

Several countries participating in the CAFF / PAME / ARIAS expert groups, including the United States, Norway and Canada, devote a great deal of resources to register invasive species. The United States are currently developing a system where non-lay people can participate in registering the occurrence of non-native species.

In relation to Arctic waters, The Norwegian Biodiversity Information Centre has conducted a very comprehensive assessment and identification of potential invasive species to, for instance, the Barents Sea and seas surrounding Svalbard. For a list of invasive and potential invasive species (door knockers) to the Barents Sea and Svalbard, see Appendix 1.

In relation to Greenland, increased focus on prevention by regulation is recommended as well as early detection in order to contain and manage the invasive species of most concern, for instance by introducing further restrictions on (local) shipping or by intensive catching of larger adult species / ??... intensive catching of adult individuals of larger species. All other things being equal, it is worth the effort to manage invasive species as early as possible and thereby preferably prevent their introduction and dispersal to new areas.

It is recommended to focus on the species identified in Tables 1, 2 and 3 as well as species identified by the Norwegian Biodiversity Information Centre for the Barents Sea.

In addition, continued focus by the CAFF / PAME / ARIAS expert groups on strategy implementation is recommended, including exchange of knowledge and data with other relevant organisational bodies on the propagation of invasive species in Arctic waters.

The Global Biodiversity Information Facility database (www.gbif.org/) does not contain information on species distributions in Greenland and Russian waters. Therefore, in order to strengthen the future work to limit the propagation and spread of invasive species in Arctic waters, consideration of how to incorporate data on Greenland and Russian waters into the GBIF-database is recommended.

Finally, development of a strategy for protection of Greenland waters against invasive species may be considered. Such a strategy could include:

- Development of a system to control that handling of ballast water complies with IMO convention requirements for ships entering Greenland waters.

- Development of a system to control that antifouling systems on ships arriving in Greenland waters are in compliance with IMO convention requirements.

- Identification of high risk shipping (e.g., ship types, shipping routes, sea areas).

- Update and maintenance of knowledge about species in risk of becoming invasive in Greenland.

- Expansion of the knowledge base for evaluating the ecological effects of potential invasive species whose impact is rated as “severe”, “high or “potentially high”.

- Development of a system for early detection / warning (e.g., inquiries and interviews with fishermen and hunters as well as biological monitoring).

- Development of management plans to combat, control and mitigate the risk for introduction and dispersal of potential invasive species as well as development of plans for control, reduction and fishing up of non-native invasive populations.

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Appendix 1 - The Alien Species List of Norway

The Alien Species List of Norway – Ecological Risk Assessment. Norwegian Biodiversity Information Centre (2018) (https://www.biodiversity.no/)

Scientific name	Species group	Impact category	Evaluation status	Area
Lithodes maja	Crustacea	Potentially high impact	Door knocker	Svalbard
Chionoecetes opilio	Crustacea	Severe impact	Established	Svalbard
Paralithodes camtschaticus	Crustacea	Severe impact	Door knocker	Svalbard
Ischyrocerus commensalis	Crustacea	High impact	Door knocker	Svalbard
Acartia tonsa	Crustacea	Low impact	Door knocker	Svalbard
Alcyonium digitatum	Hydrozoa	Low impact	Door knocker	Svalbard
Amphibalanus improvisus	Crustacea	Low impact	Door knocker	Svalbard
Ascidiella aspersa	Tunicata	Low impact	Door knocker	Svalbard
Ascidiella scabra	Tunicata	Low impact	Door knocker	Svalbard
Cancer pagurus	Crustacea	Low impact	Door knocker	Svalbard
Caprella mutica	Crustacea	Low impact	Door knocker	Svalbard
Carcinus maenas	Crustacea	Low impact	Door knocker	Svalbard
Clavelina lepadiformis	Tunicata	Low impact	Door knocker	Svalbard
Corella parallelogramma	Tunicata	Low impact	Door knocker	Svalbard
Crangon crangon	Crustacea	Low impact	Door knocker	Svalbard
Diplosoma listerianum	Tunicata	Low impact	Door knocker	Svalbard
Echinus esculentus	Echinoida	Low impact	Door knocker	Svalbard
Eurytemora affinis	Crustacea	Low impact	Door knocker	Svalbard
Gracilechinus acutus	Echinoida	Low impact	Door knocker	Svalbard
Hemigrapsus takanoi	Crustacea	Low impact	Door knocker	Svalbard
Homarus gammarus	Crustacea	Low impact	Door knocker	Svalbard
Oncorhynchus gorbuscha	Fisker	Low impact	Door knocker	Svalbard
Patella vulgata	Mollusca	Low impact	Door knocker	Svalbard
Schizoporella japonica	Bryozoa	Low impact	Door knocker	Svalbard
Austrominius modestus	Crustacea	No known risk	Door knocker	Svalbard
Molgula manhattensis	Tunicata	Low impact	Established	Jan Mayen
Paralithodes camtschaticus	Crustacea	Severe impact	Established	Finnmark
Chionoecetes opilio	Crustacea	Potentially high impact	Established	Finnmark
Ischyrocerus commensalis	Crustacea	Potentially high impact	Established	Finnmark
Oncorhynchus gorbuscha	Fish	High impact	Established	Finnmark
Oncorhynchus mykiss	Fish	High impact	Established	Finnmark

IDENTIFICATION AND RISK ASSESSMENT OF POTENTIAL INVASIVE SPECIES IN GREENLAND WATERS

Invasive species (invasive alien species) are of global conservation concern, and they may have strong, negative impacts on ecosystems, other species and valuable natural resources. So far, Arctic waters have experienced a relatively low number of biological introductions. However, observed increases in water temperatures resulting in reductions in sea ice forced by climate changes may increase shipping as well as the risk for introduction and establishment of non-native invasive species in Arctic waters. Based on a literature review and risk assessments, this report identifies species that potentially may become invasive in Greenland Arctic waters, and some of these may have potential high impacts on ecosystems and fisheries. As part of the project, Aarhus University has, in coordination with the Ministry of Environment and Food in Denmark and the Ministry of Nature and Environment in Greenland, contributed and provided input as needed to the implementation of the Arctic Invasive Alien Species Strategy and Action Plan 2017 (ARIAS), elaborated by the Arctic Council via the Conservation of Arctic Flora and Fauna (CAFF) and Protection of The Arctic Marine Environment (PAME) working groups. The report includes recommendations for the work in PAME and CAFF and for the development of a strategy to protect Greenland waters against non-native invasive species.

ISBN: 978-87-7156-514-0
ISSN: 2245-0203