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Horizon scanning of potential threats to high-Arctic biodiversity, human health and the economy from marine invasive alien species: A Svalbard case study

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Abstract

The high Arctic is considered a pristine environment compared with many other regions in the northern hemisphere. It is becoming increasingly vulnerable to invasion by invasive alien species (IAS), however, as climate change leads to rapid loss of sea ice, changes in ocean temperature and salinity, and enhanced human activities. These changes are likely to increase the incidence of arrival and the potential for establishment of IAS in the region. To predict the impact of IAS, a group of experts in taxonomy, invasion biology and Arctic ecology carried out a horizon scanning exercise using the Svalbard archipelago as a case study, to identify the species that present the highest risk to biodiversity, human health and the economy within the next 10 years. A total of 114 species, currently absent from Svalbard, recorded once and/or identified only from environmental DNA samples, were initially identified as relevant for review. Seven species were found to present a high invasion risk and to potentially cause a significant negative impact on biodiversity and five species had the potential to have an economic impact on Svalbard. Decapod crabs, ascidians and barnacles dominated the list of highest risk marine IAS. Potential pathways of invasion were also researched, the most common were found associated with vessel traffic. We recommend (i) use of this approach as a key tool within the application of biosecurity measures in the wider high Arctic, (ii) the addition of this tool to early warning systems for strengthening existing surveillance measures; and (iii) that this approach is used to identify high-risk terrestrial and freshwater IAS to understand the overall threat facing the high Arctic. Without the application of biosecurity measures, including horizon scanning, there is a greater risk that marine IAS invasions will increase, leading to unforeseen changes in the environment and economy of the high Arctic.

KEYWORDS
Arctic seas, early warning, invasive, ocean warming, pathways, risk assessment

1 | INTRODUCTION

The Arctic seas are under increasing threat from marine invasive alien species (IAS) (van den Heuvel-Greve et al., 2021), those species that have been introduced through human action outside of their native range and have the ability to spread causing damage to the environment, economy and/or human health (Hughes et al., 2020; Peyton et al., 2020). The Arctic Invasive Alien Species Strategy and Action Plan, produced by two working groups of the Arctic Council, clearly identify the threat from IAS and the need to protect the regions environment and human health (CAFF & PAME, 2017). Three key priority areas are highlighted in this strategy, including the need to improve the knowledge base, prevent the introduction of IAS and rapidly detect and respond to introductions as they occur. Unfortunately, there is relatively little baseline data available on marine IAS and their impacts in the Arctic, since they have only been seen as an increasing threat over the last decade (CAFF & PAME, 2017). In addition, a lack of effective and rapid monitoring techniques has also been attributed to the paucity of IAS information in the Arctic (van den Heuvel-Greve et al., 2021).

Svalbard, a Norwegian archipelago above the Arctic Circle (79° N) (Figure 1), is one of the most accessible regions in the Arctic, where economic activities have increased considerably in the past 20 years, with the number of ships, including cruise liners and fishing vessels, increasing by 25% between 2013 and 2019 (Stocker et al., 2020). Expansion of the tourist industry has led to the total number of cruise passengers rising by 73% from 2008 to 2018 (Stocker et al., 2020) (Figure 1). Interestingly, the number of cruise ships has declined over this period, but are now larger in size, with more passengers aboard. These ships, however, have expanded their operational season (Stocker et al., 2020) and the number of landing sites has also increased over the last 20 years from 91 in 1999 to 224 in 2019 (The Governor of Svalbard, 2022). The increase in vessel activity and expansion of the operational season around the Svalbard archipelago, therefore, poses a significant risk in terms of providing viable pathways for the introduction and subsequent redistribution of marine non-indigenous species, which have potential to become invasive (Ware et al., 2013).

Climate change is having an observable influence on our oceans (IPCC, 2023). In recent times, the Arctic has been significantly affected by increasing ocean temperatures, contributing to greater melting of sea ice and increased periods of open water (Stroeve & Notz, 2018). The Svalbard archipelago is located in a region that has seen significant ocean temperature increases in the last decade (Polyakov et al., 2020), particularly where warm Atlantic Water is carried north by the West Spitsbergen Current along the western margin of Svalbard, as well as into the Barents Sea to the east (Lind et al., 2018). Seawater temperatures typically range from −1.8°C in early spring to in excess of 5°C in coastal surface waters in late summer (Cottier et al., 2022). In line with the wider Arctic region, there is a persistent decline in sea ice cover around Svalbard, particularly in the fjordic environments (Johansson et al., 2020). It is also predicted that seawater temperatures are likely to increase in the region by around 1°C within the next 20 years (Årthun et al., 2019) and the incidence and duration of marine heat waves will become more frequent and prolonged (Huang et al., 2021; Mohamed et al., 2022). Increasing loss of sea ice coverage and rising sea water temperatures are predicted to significantly increase the risk of successful introductions of marine IAS (Ware et al., 2013). Elevated levels of sunlight caused by the reduction in sea ice cover are also predicted to result in enhanced primary production (Castellani et al., 2022; Chan et al., 2018). Consequently, climate change and the subsequent changes to the food web dynamics in the Arctic may also lead to marine IAS being able to successfully become established in the region due to increased primary productivity and the potential that some of these species may outcompete indigenous species for food (Chan et al., 2018).

Seven marine IAS have been reported in Svalbard, using eDNA samples collected from soft sediment in Kongsfjorden, northwest Svalbard (van den Heuvel-Greve et al., 2021). A number of other IAS have been reported as biofouling on ship hulls, floating debris and in ship ballast water discharged near Svalbard ports (Ware et al., 2016), although their establishment in the area has yet to be confirmed. Twenty-four marine IAS have also been highlighted by the Norwegian Biodiversity Information Centre as having the potential to become established in Svalbard within the next 50 years based on their current distribution in the bordering sea areas (https://www.artsdatabanken.no). For example, the red king crab *Paralithodes camtschaticus* has established populations in the southern Barents Sea (Falk-Petersen et al., 2011; Ruiz & Hewitt, 2009). Pacific pink salmon *Oncorhynchus gorbuscha* (Witkowski & Glowacki, 2010) and a few individuals of the snow crab *Chionoecetes opilio*, have been found in Svalbard waters since 1961 and 2017 respectively (Chan et al., 2018). Populations of previously locally extinct species, for example mussels of *Mytilus* spp. complex have also been found re-appearing in Svalbard after a thousand year absence (Berge et al., 2005), with shipping and anthropogenic flotsam, including large plastic debris, identified as potential vectors (Kotwicki et al., 2021; Leopold et al., 2019).

Remote islands are widely reported to have a disproportionate richness in biodiversity compared with adjacent continents (Russell & Kueffer, 2019), including high levels of endemism (Gray, 2019) and unique functional traits (Ottaviani et al., 2020). Marine IAS are considered an important driver of biodiversity loss on islands through their ability to significantly alter ecosystem function (Russell & Kueffer, 2019). The remoteness and small size of islands, such as Svalbard can make them vulnerable to environmental change, which can lead to significant ecological impacts (Russell & Kueffer, 2019). Marine IAS can also have substantial negative impacts on local economies (Hanley & Roberts, 2019) and human health (Tsirintanis et al., 2022). We suggest, therefore, that Svalbard is an interesting case study as it represents the vulnerability and changing environmental conditions experienced by many of the small- and medium-sized communities across the wider high Arctic.

Horizon scanning is an important element as part of a nation's biosecurity toolkit for predicting the IAS threat to a particular area

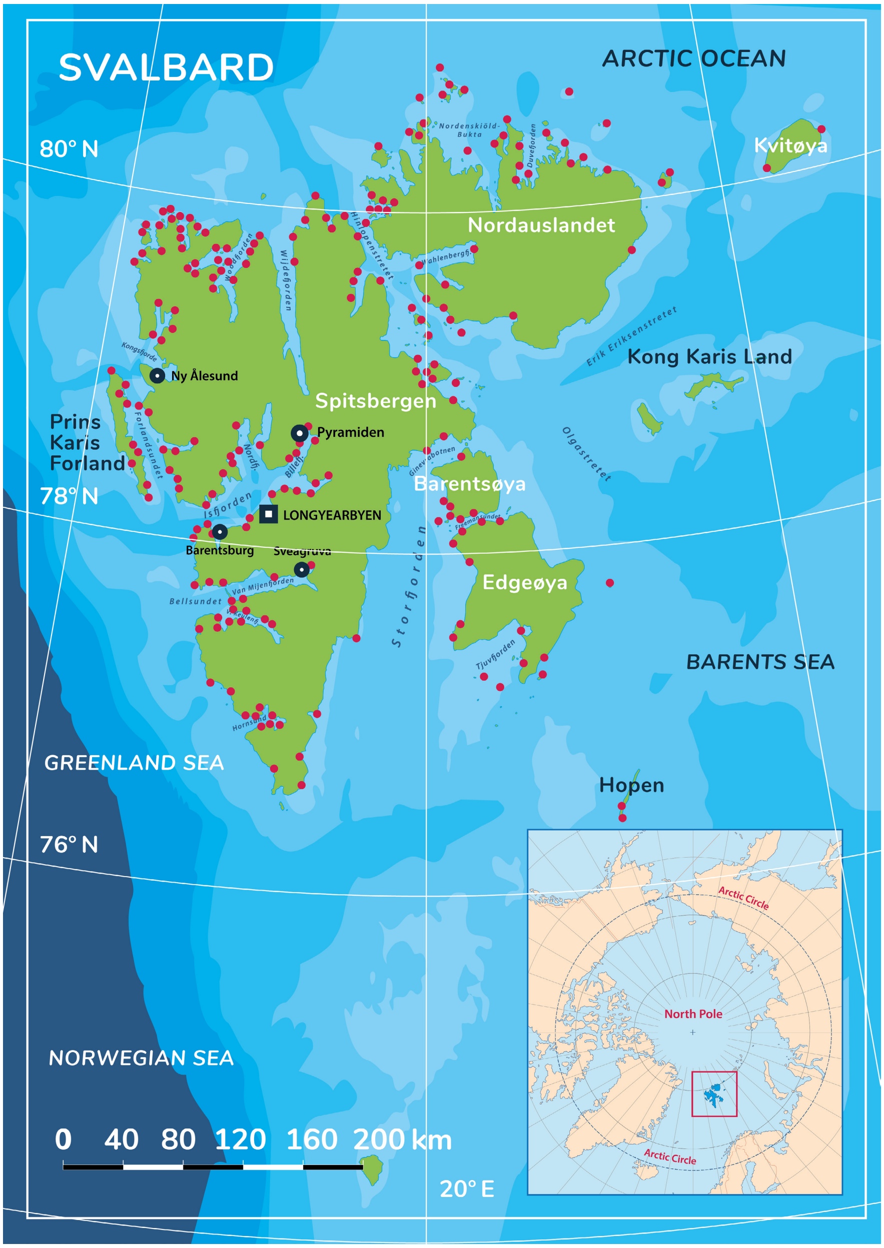

FIGURE 1 Map of the Svalbard archipelago showing the location of ports (black dots) and cruise ship landing sites, as highlighted by Hagen et al. (2012) (red dots). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

over a given period into the future (Roy et al., 2014). A list of potential 'door-knockers' (e.g. IAS that are likely to be introduced to Svalbard in the next 50 years) has been produced (Norwegian Biodiversity Information Centre, 2020). This list, however, was not based upon the broad geographical range that has been used for previous horizon scanning exercises in the United Kingdom (Roy et al., 2014), the EU (Roy et al., 2019), the Antarctic Peninsula Region (Hughes et al., 2020) and several oceanic islands (Dawson et al., 2022). It, therefore, has the potential to exclude certain species that could pose a risk to the biodiversity, economy or human health. The horizon scanning exercise used in this study, therefore, used the Svalbard archipelago as a case study to information further studies across the wider high Arctic. The exercise is based on both expert opinion and a consensus approach used in similar exercises for other parts of the world (Hughes et al., 2020; Peyton et al., 2020; Roy et al., 2014), to develop a ranked list of marine IAS, which are currently absent or have had the occasional sighting, but are considered to potentially arrive, establish and have a negative impact on biodiversity, economy and human health in Svalbard over the next 10 years. This exercise also highlighted the potential high-risk introductory pathways for each of the IAS, to aid future biosecurity management decisions for the archipelago and the wider high Arctic.

2 | MATERIALS AND METHODS

Experts in taxonomy, horizon scanning methodology and Svalbard's marine environment based in the United Kingdom, Ireland, Lithuania and Norway met for a virtual workshop (22 June 2022), to carry out a horizon scanning exercise to identify marine IAS, that pose the highest risk to the biodiversity, human health and economy of the archipelago over the next 10 years. The methodology using the consensus approach was an adapted version from Roy et al. (2014) and involved the following four steps:

2.1 | Selection of expert group

The experts were selected to provide expertise across the Arctic region and globally on the taxonomy of marine IAS, on the Svalbard environment and on the horizon scanning process (Table S1). A leader was assigned to the group to provide coordination, record keeping and discussion facilitation between members before, during and after the workshop.

2.2 | Production of preliminary lists of marine IAS

Prior to the workshop, a preliminary list of marine IAS, which were considered to potentially pose a high risk based on likelihood of arrival, establishment and potential negative impact on biodiversity, human health and the economy in Svalbard over the next 10 years, was compiled through email exchanges among the experts over a period of 6 months. The list was prepared through in-depth literature searches, including scientific journal articles (e.g. Chan et al., 2018; Husa et al., 2022; van den Heuvel-Greve et al., 2021; Ware et al., 2016), reports, risk assessments (e.g. GBNNS Risk Assessments), invasive species databases, such as www.artsdatabanken.no, AquaNIS, CABI, GBIF and WoRMS, EMODnet Arctic—aliens webpage and by group members' own knowledge.

The geographical range for consideration was global, however, only species absent from Svalbard, seldom recorded and/or identified in environmental DNA samples in the archipelago were considered. Species that are known to have an impact on biodiversity and/or the economy in regions with similar climatic conditions to Svalbard or have been associated with potential pathways of trade and travel and/or anthropogenic debris (e.g. plastic flotsam) in and around the region, were also considered. The pathways were based on the Convention of Biological Diversity (CBD) classifications (CBD, 2014) (Table 1). Species with populations in mainland Norway or with populations that have been previously recorded from Svalbard were also included. Excluded from the preliminary list were microbial pathogens, including bacteria, fungi or other microorganisms, due to gaps in knowledge and not necessarily due to the lack of importance for these species in terms of invasion and risks to biodiversity and/or the economy. Species that were deemed to arrive from their native range by natural spread, unaided by humans, were also excluded from the list. Positive impacts, particularly economic, were discussed, but not included in this exercise, since the main aim was to highlight the high-risk species with the greatest negative impacts.

The 10-year timescale for the exercise was based on previous horizon scanning exercises (Roy et al., 2020) and, although limiting in terms of relevance to longer term climatic changes in the region, it was deemed a realistic period of time to enable biosecurity measures to be developed and implemented.

TABLE 1 Convention of Biological Diversity pathway categories and subcategories (CBD, 2014) selected for their relevance to the marine environment and for the Svalbard Archipelago.

Category	Subcategory	Code
Release	Fishery in the wild	R_FHRY
	Conservation in wild	R_CON
	Release for use	R_USE
	Other release	R_OTR
Escape	Ornamental	E_ORN
	Research	E_RES
	Live food and live bait	E_LFB
	Other escape	E_OTR
Contaminant	Parasite of animals	C_PAR_ANI
	Parasite of plants	C_PAR_PLT
	Habitat material contaminant	C_HAB
	Other contaminant	C_OTR
Stowaway	Ship excluding ballast water or hull fouling	S_SHIP
	Ballast water	S_BALL
	Hull fouling	S_HULL
	Other stowaway	S_OTR
Unaided	Natural dispersal	U_NAT

2.3 | Prioritisation of species

The species on the preliminary list were subsequently prioritised by the experts using a scoring system based on the likelihood of: (i) arrival; (ii) establishment; and (iii) extent of negative impact on biodiversity, human health and the economy of Svalbard (Table 2).

Each of these categories was given a score between 1 and 5 based on the criteria as outlined in Roy et al. (2020). A score of 1 signifies little effect or minimal likelihood/impact, while a score of 5 signifies a significant effect or very high likelihood of arrival, establishment or impact (see Roy et al., 2020, for more details). The scores from each expert were then compiled and discussed at the workshop. Each species' overall likely impact, for ranking purposes only, was calculated by multiplying the scores for each criterion together, so a separate overall score was achieved for environmental, human health and the economy. A maximum score of 125 for overall risk was, therefore, possible. Confidence levels of high, medium and low were also assigned to each score based on the experts' confidence in the supporting evidence.

2.4 | Consensus approach

The workshop provided the expert team with the opportunity to finalise the scoring of the species on the preliminary list and to collaboratively rank them based on their final overall scores in each of the three categories (i.e. biodiversity, human health and economy). During this process, experts were encouraged to share their

TABLE 2 Examples of impact relevant to the marine environment used in the horizon scanning exercise.

Impact category	Examples of impact
Environment	Parasite, pathogen or pest on native species, predation, herbivory/grazing of native species, hybridisation, parasite, pathogen or pest vector, habitat change or loss, biodiversity loss, food web changes, nutrient regime or alterations, changes to ecosystem services and/or hydrological cycles, competition, loss or impact on keystone species and/or threatened or endangered species, toxic to native species
Economy	General management costs, decline in fisheries or increased costs for harvesting and processing, changes to wildlife habitat (e.g. fishery spawning grounds), cost of changes to environment, impact on navigation and/or tourism, increased health care costs
Human health	Human pathogen or parasite, toxic or poisonous to humans, skin lacerations if touched

opinions and justify their scores. Further refinement of the scores and moderation of the list was then undertaken over the following few months. Any changes to the overall ranking in each of the categories were only done after consideration of the evidence from the appropriate expert and in full consensus by the team. This approach enabled an agreed ranked list of potentially high risk, marine IAS to be produced for each impact category.

3 | RESULTS

One hundred and fourteen species were considered in the preliminary list for further review at the consensus workshop (Table S3). Seven species were selected from this initial list as presenting a moderate to high risk of being introduced, establishing and having a negative impact on the biodiversity of the Svalbard archipelago (Table 3). Following the same selection process, five species were identified as having a potential negative impact on the economy of the region (Table 4). None of the species considered in the preliminary list were deemed to have any potential risk to human health. All the workshop participants agreed that this list was representative of the consensus approach adopted.

Three predators were included in the top seven species deemed to have the highest risk to biodiversity in Svalbard, including two large decapod crab species *Paralithodes camtschaticus* and *Chionoecetes opilio* and the pink salmon *Oncorhynchus gorbuscha*. Suspension feeders also ranked highly in the final list, including one bryozoan and three ascidians (two colonial and one solitary species) (Table 3). Two suspension feeders and three predators were found to have the highest risk to Svalbard's economy, based on their previous history of economic impact, arising from the costs of biofouling (Table 4).

3.1 | Pathway analysis

The top seven species ranked as the highest risk to biodiversity in Svalbard are predominantly native to the Northern Hemisphere. Three of these species, however, *Molgula manhattensis*, *Botrylloides violaceus* and *Didemnum vexillum*, have also been reported from numerous locations in the Southern Hemisphere. The pathway of arrival to Svalbard for the majority of the top seven species is most likely to be via vessels. Vessels, such as cruise liners, fishing boats and supply ships are able to cover extensive distances and associated species will either be transported as biofouling via their attachment to their hulls (attributed to 71% of the species in the top seven), through the containment of one or more life-stages within their ballast water (57%) and/or as by-catch release (29%). The extensive drift of flotsam may also enable range expansions of biofouling species. Two of the decapod crab species *Paralithodes camtschaticus* and *Chionoecetes opilio*, however, may also be able to spread naturally to Svalbard from their current introduced range either through dispersal of their larvae, via active walking across the seabed or from fishery discards. The pink salmon *Oncorhynchus gorbuscha* though is most likely to spread to Svalbard unaided by anthropogenic means, as it continues to spread southwards through the Arctic from its initial point of introduction in the Barents Sea.

Four of the top five species ranked as the highest risk to the economy in Svalbard were also included in the top seven for highest risk to biodiversity. The isopod *Limnoria lignorum*, however, was only considered as high risk to the economy in Svalbard, since it has spread to other locations worldwide causing considerable damage to coastal wooden piers and pilings. Since Svalbard is in the pathway of a strong northwards flowing current from the Atlantic, it is likely that this species may arrive in the archipelago in floating wooden debris.

4 | DISCUSSION

4.1 | Expected arrivals and their possible impacts

In this horizon scanning exercise, the greatest immediate threat to the native biodiversity of this archipelago was from three predators and four suspension feeders, all of which have been extensively documented as marine IAS in Europe. Five of these species have been reported as established in the Northern

TABLE 3 The highest risk marine invasive alien species for Svalbard in the next 10 years based on likelihood of arrival (a), establishment (b) and negative impact on native biodiversity (c). For pathway of arrival (R_OTR, release other—discards; S_Ball, ballast water; S_Hull, hull fouling; U_Nat, unaided natural spread [species arriving from previous invaded regions]). Confidence level in overall score (H, high; L, low; M, medium).

Rank	Species	Common name	Taxonomic group	Functional group	Native range	Pathway of arrival	*A*	*B*	*C*	Overall score ($A \times B \times C$)	Confidence	Potential negative impact
1	*Paralithodes camtschaticus*	Red king crab	Arthropoda: Malacostraca	Predator	NW, NE Pacific	U_Nat, S_Ball, R_OTR	5	5	5	125	H	Reduce local benthic species diversity through predation
2	*Chionoecetes opilio*	Snow crab	Arthropoda: Malacostraca	Predator	N Pacific, NW Atlantic	U_Nat S_Ball, R_OTR	5	5	4	100	H	Reduce local benthic species diversity through predation
3	*Schizoporella japonica*	Orange ripple bryozoan	Bryozoa: Gymnolaemata	Suspension Feeder	NW Pacific	S_Hull, S_Ball	5	5	3	75	L	Outcompetes native species and can alter community composition
4	*Oncorhynchus gorbuscha*	Pink salmon	Chordata: Actinopteri	Predator	NW Atlantic, N, NE Pacific	U_Nat	5	4	3	60	M	Competition for resources, and hybridisation with native fish
=5	*Molgula manhattensis*	Sea grapes	Chordata: Ascidiacea	Suspension feeder	NE Atlantic, circum-global	S_Hull	5	5	2	50	M	Outcompetes native species and can alter community composition
=5	*Botrylloides violaceus*	Violet tunicate	Chordata: Ascidiacea	Suspension feeder	W Pacific	S_Hull	5	5	2	50	L	Outcompetes native species and can alter community composition
7	*Didemnum vexillum*	Carpet sea squirt	Chordata: Ascidiacea	Suspension feeder	NE Atlantic	S_Hull, R_OTR	4	3	4	48	M	Outcompetes native bivalve species and can alter community composition

TABLE 4 The highest risk marine invasive alien species for Svalbard in the next 10 years based on likelihood of arrival (a), establishment (b) and negative impact on the economy (c). For pathway of arrival (R_OTR, release other—discards; S_Ball, ballast water; S_Hull, hull fouling; S_OTR, stowaway other—anthropogenic debris; U_Nat, Natural spread [species arriving from previous invaded regions]). Confidence level in overall score (H, high; L, low; M, medium).

Rank	Species	Common name	Taxonomic group	Functional group	Native range	Pathway of arrival	A	B	C	Overall score (A × B × C)	Confidence	Potential negative impact
=1	*Paralithodes camtschaticus*	Red king crab	Arthropoda: Malacostraca	Predator	NW, NE Pacific	U_Nat S_Ball, R_OTR	5	5	2	50	L	Damage to fishing gear and the spread of parasites to commercially fished species
=1	*Chionoecetes opilio*	Snow crab	Arthropoda: Malacostraca	Predator	N Pacific, NW Atlantic	U_Nat S_Ball, R_OTR	5	5	2	50	L	Impact on commercial benthic fisheries of native stocks
=1	*Molgula manhattensis*	Sea grapes	Chordata: Ascidiacea	Suspension feeder	NE Atlantic, circum-global	S_Hull	5	5	2	50	L	Fouling of infrastructure leading to increased maintenance costs
=2	*Oncorhynchus gorbuscha*	Pink salmon	Chordata: Actinopteri	Predator	NW Atlantic, N, NE Pacific	U_Nat	5	4	2	40	L	Impact on commercial fisheries of native stocks
=2	*Limnoria lignorum*	Gribble	Arthropoda: Malacostraca	Suspension feeder	Unknown	S_Hull, S_OTR	5	4	2	40	L	Damage to wooden infrastructure (e.g. piers, wharfs etc)

Hemisphere; including *Paralithodes camtschaticus*, *Chionoecetes opilio*, *Schizoporella japonica*, *Oncorhynchus gorbuscha* and three have been reported globally (i.e. *Molgula manhattensis*, *Botrylloides violaceus* and *Didemnum vexillum*).

The top two marine IAS posing a high risk to native biodiversity in Svalbard were large decapod crabs, the red king crab *Paralithodes camtschaticus* and the snow crab *Chionoecetes opilio*. These two species have a high fecundity, are long lived and highly mobile. They are able to tolerate the cold conditions and they feed on wide range of prey in subtidal habitats, which can lead to a reduction in benthic diversity and impacts on ecosystem function (Oug et al., 2018). No other predators in the archipelago have large crushing claws, suggesting that many taxa currently able to escape predation may be vulnerable to these new arrivals (Falk-Petersen et al., 2011). *Paralithodes camtschaticus*, apart from carrying an amphipod parasite, may also indirectly transmit trypanosome infections to wild cod populations (Hemmingsen et al., 2005). Both crab species have been recorded in other Arctic regions (Chan et al., 2018; van den Heuvel-Greve et al., 2021), having been initially introduced to the Barents Sea in the 1960s and 1970s from its native range in the North Pacific with the intention of developing a fishery (Jørgensen et al., 2004). The snow crab *Chionoecetes opilio* was also introduced to the Barents Sea and has similarly expanded its range with some singular sightings from Svalbard, including a record from the northwest coast (Lorentzen et al., 2018), which may have originally resulted from a catch discard.

Four ascidians were also identified as high-risk IAS to biodiversity in Svalbard. These fouling species are all well-known marine IAS elsewhere and are commonly found on vessel hulls. The colonial species typically originate from the western Pacific, such as the bryozoan *S. japonica* and the ascidian *B. violaceus* or are cosmopolitan (i.e. found globally). These species are highly competitive, rapidly overgrowing both primary and secondary natural (e.g. bivalves, macroalgae) and artificial substrates (e.g. vessel hulls), forming extensive colonies and frequently dominating fouling communities (Chen et al., 2017; Cottier-Cook et al., 2019; Dijkstra & Harris, 2009; Järnegren et al., 2023; Loxton et al., 2017). Long range transportation of these species has been via vessels (i.e. ballast water and ship hull fouling) and aquaculture stock (Minchin, 2007; Ryland et al., 2014).

The Pink salmon *Oncorhynchus gorbuscha* was ranked fourth in the top seven marine IAS and was the only vertebrate identified with the potential to have an impact on biodiversity. This species has a wide native range in the northern Pacific and as a result of multiple introductions into northwestern Russia, it has subsequently spread to Norwegian waters (Sandlund et al., 2019). Vagrants of this species have been recorded periodically in the Svalbard area since 2002, suggesting that this species can range far from the Norwegian mainland (Petryashov et al., 2002; Sandlund et al., 2019), but is not yet known to reproduce in the area. This species has also been reported as being extremely adaptable in both its life history and ecology to fit in with local conditions (Sandlund et al., 2019). It is, therefore, likely that this species may become established and reproductively successful in Svalbard waters in the next 10 years and have an impact on the native biodiversity through competing for food with other fish species in the area (Nielsen et al., 2013).

Five species were identified as having an impact on the economy of Svalbard, albeit at a moderate (=2) level. They were, however, also highlighted in the horizon scanning exercise as species of concern due to their high likelihood of arrival and establishment in the next 10 years. These species included three predators and two omnivores. The three predators, the Pink salmon *O. gorbuscha*, the red king crab *P. camtshaticus* and the snow crab *C. opilio* have been discussed in relation to their potential impact on biodiversity. *P. camtshaticus* has been reported to impact the profit margins of the fishing industry by damaging nets, through entanglement and reducing longline catches due to their removal of bait from the longline hooks (Jørgensen & Nilssen, 2011). *Chionoecetes opilio* has been reported to feed upon significant quantities of commercial bivalve stocks (Gebruk et al., 2020; Holte et al., 2022; Zakharov et al., 2021). Establishment of these crab species, likely coincident with enhanced fishing activities around Svalbard as Atlantic cod and other species increase in the region, will increase conflict with fisheries. The pink salmon *O. gorbuscha* also have the potential to have an impact on local commercial fisheries, potentially competing with local native species for food resources (Sandlund et al., 2019). In mainland Norway, this species has a 2-year life history, whereby they leave the fjords as smolt after approximately 6 months in the rivers and then grow to adulthood in only 1.5 years. This constitutes heavy feeding in coastal waters, perhaps in conflict with other commercial species.

The two suspension feeders include a solitary ascidian *Molgula manhattensis* and an arthropod species *Limnoria lignorum*. The former can rapidly dominate the fouling community, forming extremely dense populations (Otsuka & Dauer, 1982) and has been reported to impede trawling activities (Cohen & Carlton, 1995). The wood-boring *L. lignorum* can weaken wooden structures, such as wharfs, piers and vessel hulls (Borges et al., 2014). Svalbard has numerous wooden piers used in the construction of piers for the former coal mining industry and also for the ports, including one that was infested with the shipworm *Teredo navalis*, a bivalve mollusc, in Longyearbyen a few years ago (Kintisch, 2016). Shipworms have also been recovered from driftwood (Siberian Larch) travelling across the central Arctic Ocean in Rijpfjorden, northern Svalbard (Kintisch, 2016), so the introduction of *L. lignorum* and other wood-boring species could potentially be a threat to the economy of this archipelago within the next decade.

No foreseen impact was reported on the health of the Svalbard human population by any marine IAS identified as part of this horizon scanning exercise. It is important to note, however, that microorganisms were not included in this exercise, due to the lack of information on these species and this remains a critical knowledge gap for predicting the impacts of marine IAS.

4.2 | Changes in pathways of introduction: Interaction between natural and anthropogenic factors

The strong, advective nature of the northwards flowing current from the Atlantic towards Svalbard (Berge et al., 2005) both transports organisms and leads to increasing seawater temperatures and reduced ice cover. This current has already facilitated the northwards spread and establishment of species native to more southern Arctic waters, for example the blue mussel (Berge et al., 2005), the Atlantic mackerel (Berge et al., 2015) and the Atlantic snake pipefish (Fleischer et al., 2007). It is also likely to facilitate natural processes, such as rafting on driftwood or seaweed, or through the dispersal of pelagic life-stages (Descôteaux et al., 2022; Kotwicki et al., 2021). It is highly likely, therefore, that this current, in combination with the rising sea temperatures predicted for the Svalbard archipelago and the wider Arctic (IPCC, 2023) will facilitate the establishment of other non-indigenous marine species (Alabia et al., 2023). Species distribution models, particularly those that allow for seasonal trends (El-Gabbas et al., 2021), are now required for the region to more accurately predict which non-indigenous species are likely to be introduced and their establishment potential.

With the accelerating increase in anthropogenic substrata, such as plastic debris over the last decade (e.g. 100-fold in the South Atlantic alone, Barnes et al., 2018), it is also highly likely that this pathway will become a more recognised route of introduction in the future (Haram et al., 2023). Unfortunately, to date only a few studies have looked at this potential new introduction pathway in Arctic waters (Kotwicki et al., 2021; Ware et al., 2016; Węsławski & Kotwicki, 2018) and there is no information on the proportion of non-indigenous species arriving on natural versus plastic rafting materials. It has been suggested though that certain species attached to floating plastic have a higher chance of surviving lengthy voyages than those linked to natural flotsam, which can absorb water, degrade and subsequently lose buoyancy (Thiel, 2003).

Still, the major pathway for the introduction of marine IAS at present is shipping, either via discharges of ballast water and/or hull fouling. While Norway has now ratified the Ballast Water Convention, logistical and technical challenges still exist, with many ships accessing Arctic waters yet to fully comply with the ballast water regulations that took effect in 2017 (Ware et al., 2016). There is still the risk, therefore, of marine non-indigenous species being introduced into ports in the Arctic, including Svalbard via this pathway, although it is likely that many of these species will be unable to survive (Balaji et al., 2014; Ware et al., 2016). The International Maritime Organisation (IMO) has also introduced voluntary guidelines to minimise the transfer of IAS by biofouling (IMO, 2011), however, since these guidelines are not mandatory and there are currently no requirements to inspect the vessels entering ports, such as those in Svalbard, this pathway may actually present one of the key threats to marine biodiversity and the economy in the high Arctic.

Data from cruise liners are routinely reported and although there has not been any significant increase in the number of these vessels over the last 20 years, there has been an extension to the season and a significant increase in the landing sites over this period (The Governor of Svalbard, 2022). As cruise vessels typically anchor or berth alongside wharfs and hold position for several hours while their passengers are ashore, marine IAS are, therefore, given the opportunity to be released into the new environment. In addition, supply vessels may be present in ports for extended periods, thereby providing opportunities for the dispersal of marine IAS attached to their hulls (McCarthy et al., 2022; Saebi et al., 2020).

4.3 | Increasing vulnerability of Arctic habitats to biological invasions

The high Arctic is considered to be a pristine environment when compared with other areas in the Northern Hemisphere. It is also considered to be one of the least invaded marine ecosystems globally, with the exception of Antarctica (Hughes et al., 2020). Sixteen marine IAS have already been identified in the Svalbard archipelago and surrounding waters in the last 10 years (see Table S2). With the rapid loss of sea ice, increases in ocean temperature and salinity and a significant rise in anthropogenic activities, further appearances of marine IAS and those extending their ranges naturally northwards are inevitable.

The remoteness of the Arctic and the harsh environmental conditions, however, have made it more resistant to propagule pressure (i.e. the number, frequency and quality of propagules). IAS propagules, including vegetative reproductive organs, tissues used in asexual reproduction, gametes, seeds, dormant spores and gravid females have the ability to establish new populations (Olenin et al., 2017). Propagule pressure is accelerating due to the warming of the Arctic and increased human activity that is giving organisms new paths to travel. Depending on how many propagules survive, some Arctic aquatic habitats will be more vulnerable to introductions than others. Establishment may follow from increased arrival events, or a large propagule release from one event (Johnston et al., 2009). Factors facilitating the success of propagules include altered disturbance regimes, low levels of environmental stress and high resource availability (Alpert et al., 2000). For example, a consequence of the warming of the coastal Arctic is the development of periglacial lagoons, which have appeared in areas where glaciers have retreated from the sea inland (Søreide et al., 2020). Periglacial lagoons are increasingly offering new and diverse habitats for aquatic organisms, from microorganisms to fish and some marine mammals (Søreide et al., 2020).

4.4 | Management constraints

A full assessment, based on a theoretical understanding, regular monitoring, modelling, as well as political will, is required for the management of biological invasions, although this is rarely achieved due to limited resources. In addition, the difficulty in reliably identifying certain organisms to species level without the use of molecular tools (e.g. the *Mytilus* complex), the lack of information on microscopic IAS, such as parasites, fungi and microalgae and the lack of knowledge on marine biota, particularly in the Arctic (Deb & Bailey, 2023), significantly hampers monitoring and surveillance programmes (Hughes et al., 2020). Recent advances in environmental DNA metabarcoding techniques are now enabling the early detection of some marine IAS in the Arctic (van den Heuvel-Greve et al., 2021; Ware et al., 2016), although ground-truthing and repeated sampling is still required to determine whether these species will survive, become established and subsequently cause any impact.

The paucity of information on the likelihood of establishment and impact of many of the species in our extended and top seven and five lists for biodiversity and economic impacts respectively, also means that the confidence levels were either medium or low, with the exception of the top two ranked species, as some species may have already become locally established (Tables 3 and 4). Despite these uncertainties, however, horizon scanning provides a first step in the management of IAS, in which species are both risk assessed and prioritised, so the limited resources can be more targeted (Hughes et al., 2020; Roy et al., 2014).

5 | CONCLUSIONS

The Arctic Invasive Alien Species Strategy and Action Plan clearly indicate the threat from IAS in the Arctic, and the need to protect the region's environment and human health. Until now, however, minimal progress has been made in the high Arctic, including Svalbard in the development of biosecurity and surveillance procedures for marine IAS. The implementation of biosecurity measures when transporting cargo or personnel will always carry a significant cost. This cost of introducing management measures pre-invasion or in the early stages of an invasion is often insignificant, however, when compared with the substantial expense of eradicating or managing an outbreak of a marine IAS once established (Hughes et al., 2020).

The Svalbard archipelago is an informative case study, representing the high Arctic, since it is exposed to rapid environmental change and experiences pressures from the main IAS introductory pathways. To its advantage, Svalbard, as in the case of many other areas in the Arctic, only has a few ports of entry and strict regulations are already in place on shore landings and no-go areas. Ballast water exchange from ships is also restricted, as directed by the Ballast Water Convention (IMO, 2013). These measures can help prevent and mitigate IAS arrival and establishment, particularly species transported in ballast tanks. Biosecurity planning, though can be further strengthened by horizon scanning, which can identify likely non-indigenous species, other pathways of introduction and the risk that certain species can pose to biodiversity, the economy and human health. We suggest that horizon scanning is a useful and necessary tool within the application of biosecurity measures in the high Arctic, including Svalbard, as it identifies the species, pathways and potential negative risks that need specific attention in a defined area. It should, however, be noted that for species that may have additional positive economic impacts (Bonanno, 2016), for example, the red king crab *P. camtschaticus* (Lorentzen et al., 2018), separate assessments would be advisable taking into account their positive impacts alongside their ecological threats as IAS. This tool, alongside early warning systems, such as AquaNIS, the information system dedicated to aquatic non-indigenous and cryptogenic species (http://www.corpi.ku.lt/databases/index.php/aquanis), could be used, however, as the crucial first step for a more balanced management strategy, which would strengthen surveillance and provide further opportunities to identify the high-risk species.

AUTHOR CONTRIBUTIONS

Elizabeth J. Cottier-Cook: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing – original draft; writing – review and editing. **Jude Bentley-Abbot:** Data curation; investigation; writing – original draft. **Finlo R. Cottier:** Conceptualization; investigation; writing – original draft; writing – review and editing. **Dan Minchin:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; writing – original draft; writing – review and editing. **Sergej Olenin:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; validation; writing – original draft; writing – review and editing. **Paul E. Renaud:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; validation; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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