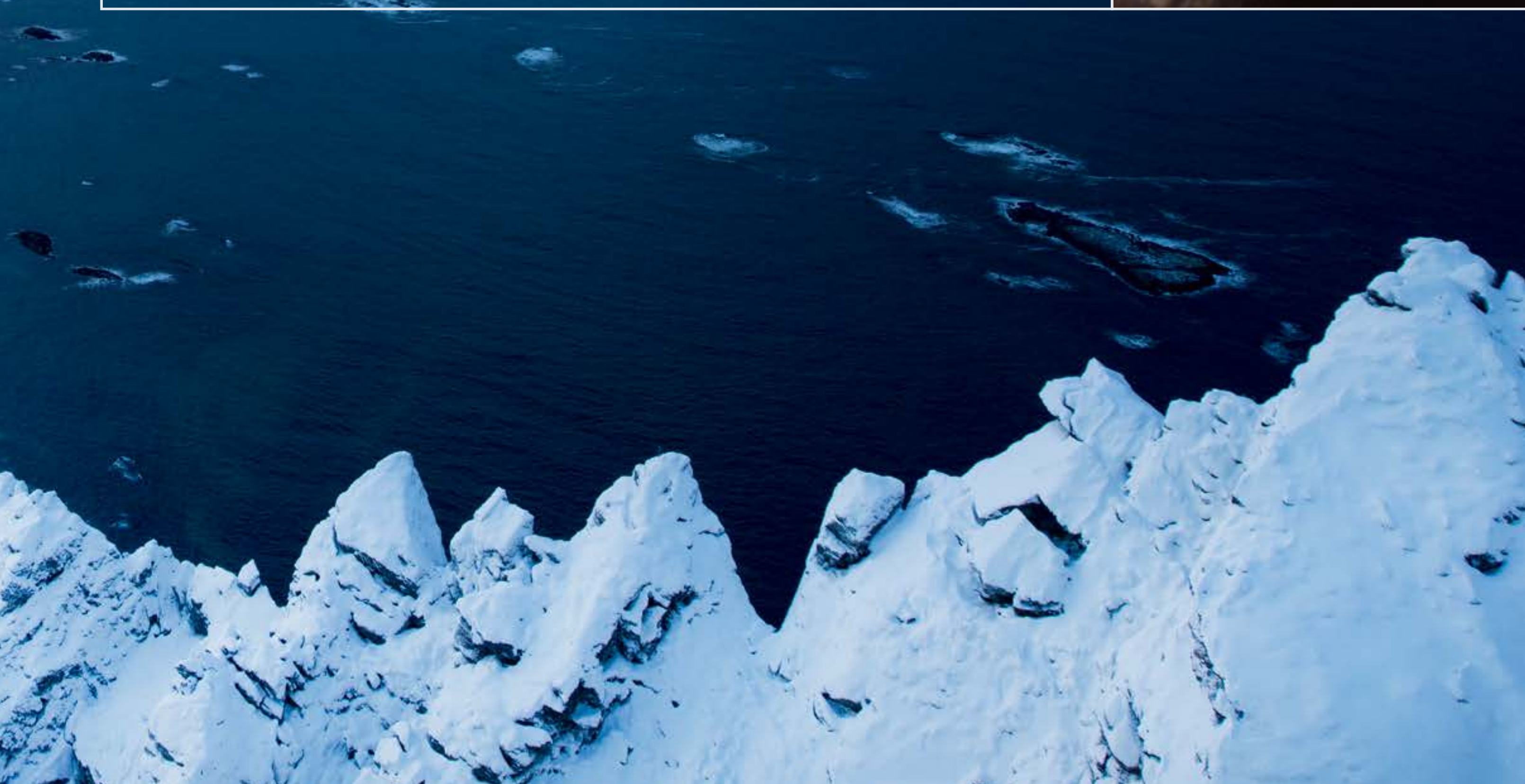
INVASIVE ALIEN SPECIES IN THE CHANGING ARCTIC

This brief summarizes the current status and emerging threats related to invasive alien species in the Arctic with respect to ecological, economic and cultural values, and outlines some of the options for their effective prevention and management.



ARCTIC COUNCIL

CAFF
Conservation of Arctic Flora and Fauna

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Protection of the Arctic Marine Environment

PHOTO/IMAGE: RIKU LUMIARO

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Invasive Alien Species in the Changing Arctic

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KEY MESSAGES

The presence and potential impacts of invasive alien species in the Arctic are on the rise due to the warming climate and the associated increase in accessibility and human activity.

If unmanaged, invasive alien species have the potential to threaten Arctic ecosystems and livelihoods and cause serious economic harm. Importantly, they pose a risk to the wellbeing of people, especially Indigenous Peoples, as well as local communities reliant on subsistence harvesting.

Limiting the risks and negative impacts of invasive alien species is achievable through decisive management actions that combine multiple methods. Prevention and preparedness are often the best and most cost-effective options.

International cooperation and regional coordination are critical for addressing the transboundary nature of invasive species in the Arctic.

Additionally, effective management of invasive alien species requires collaboration with Indigenous Peoples as well as other local actors and communities. Education, awareness raising, and public engagement are also vital to address this problem.

INVASIVE ALIEN SPECIES – A GROWING CONCERN IN THE ARCTIC

PHOTO/IMAGE: RIKU LUMIARO

Invasive alien species are widely recognized as a major driver of biodiversity loss in aquatic and terrestrial ecosystems globally[1,2] (definitions in BOX 1). They contribute to ecosystem degradation and species endangerment by changing physical ecosystem properties and ecological interactions[3,4]. Alongside the ecological impacts, invasive alien species often negatively affect nature's contribution to people and quality of life[4]. Globally, invasive alien species have incurred significant economic costs (at least $1.738 billion USD since 1970) that are expected to continue to increase in the future[5,6]. Costs include direct effects of invasive alien species such as loss of crops, land alteration, infrastructure damage and income reduction, and the costs of management actions.

Not all new species in an ecosystem are alien species, as with global warming more southern species are experiencing natural range shifts northwards (e.g., orcas, capelin). Not all alien species are harmful; some invasive alien species are even of value to society, sometimes of commercial value (e.g., the red king crab in the Barents region)[3,7]. Despite some positive outcomes, the majority of the impacts of invasive alien species generally, as well as those reported by Indigenous Peoples and those reported by local communities related to autonomy, cultural identity, and quality of life, are negative[4,5]. These negative impacts arise through, for example, increased labor, compromised access to clean water, and reduced mobility or economic opportunities including harvesting[5]. By competing with and replacing culturally and economically significant native species, invasive alien species can impose changes in traditional harvesting practices[8] (Case Study 1). Still, the perceptions by Indigenous Peoples and by local communities of invasive alien species can be varied and, in some cases, they are considered a valued part of nature[4,9]. Invasive alien species can create new sources of income for local and indigenous communities, although often this occurs through necessity rather than choice[4,8].

BOX 1

Biological invasion – a process that transports (moves) and introduces a species outside of its natural range, intentionally or unintentionally, through human activities to new regions where it may become established and spread[4].

Alien species – A species whose presence in a region is attributable to human actions, intentional or unintentional, that have enabled it to overcome the barriers that define its natural range[4]. Commonly used synonyms include exotic, introduced, non-indigenous, and non-native species[13].

Native species – A species (animal, plant, or other organism) that remains within its natural range, including range shifts without human involvement[4].

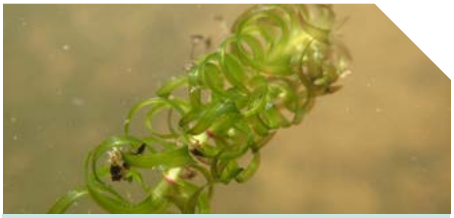
Invasive alien species – Species that are not native to a given ecosystem (that is, their presence is due to intentional or unintentional escape, release, dissemination, or placement into that ecosystem as a result of human activity) and which may cause economic or environmental harm, including harm to subsistence species and activities or harm to human health[3].

Definitions used here following IPBES[4] and CAFF/PAME[3] as cited.

Invasive alien species have been an issue of relatively limited concern in the Arctic region until recently[3] because globally, the number of alien species decreases from the tropics towards the poles, and the survival of southern species in the Arctic was thought to be limited[10]. This is likely to change with the ongoing transformation of the Arctic due to the warming climate and increasing human activity that directly and indirectly increases the possibility of future introductions of alien species[3,9,11,12]. For example, the number of alien plant species in the Arctic increased by 80% from 2013 to 2019 (to 341 species)[11]. Early introductions of alien species in Arctic regions were largely intentional (e.g., nootka lupine in Iceland for reforestation and erosion control), in many cases without a full understanding of the potential ecosystem impact[10]. Recent and predicted introductions are increasingly unintentional, such as those that occur via maritime traffic, and therefore more difficult to detect and contain[10]. As Indigenous Peoples in the Arctic often depend on local flora and fauna for subsistence and their cultural and spiritual value[3,12], they are likely to be impacted by invasive alien species directly. The limited detailed information on the baseline of species presence in the Arctic is cause for concern[3,11]. However, in many cases this can be alleviated by considering Indigenous Knowledge[4].

SELECTED INVASIVE ALIEN SPECIES AND SOME EXAMPLES OF THEIR PRESENCE IN THE ARCTIC

EXAMPLES OF INVASIVE PLANTS



WATERWEED
(ELODEA SP.)

	Impact
Native area southern North America and South America ↓ **Alien area** USA (Alaska), Kingdom of Denmark (Faroe Islands), Sweden, Finland	Compromises water quality; Concern for native salmon; Clogs waterways

Introduction: Introduced to Alaska through aquarium trade, spread by boats and floatplanes

NOOTKA LUPINE
(LUPINUS NOOTKATENSIS)

	Impact
Native area North America ↓ **Alien area** Iceland, Kingdom of Denmark (Greenland), Norway, Sweden	Displacement of native plants; Reduced native species diversity; Improves reclamation of degraded areas

Introduction: Introduced to Iceland in for soil amelioration and reforestation. Spread accidentally to Greenland and Scandinavia

HOGWEED
(HERACLEUM SOSNOWSKYI)

	Impact
Native area eastern Caucasus region ↓ **Alien area** Russia	Dermatitis caused by phototoxicity; Exclusion of native species; Increases vulnerability to invasions

Introduction: Introduced to former USSR as a fodder crop in the 1940s

PHOTOS: WATERWEED: JANNE TOLONEN, CC-BY-NC-SA-4.0, VIERASLAJIT.FI, NOOTKA LUPINE: RIKU LUMIARO, HOGWEED: RIKU LUMIARO

EXAMPLES OF INVASIVE VERTEBRATES

PINK SALMON
(ONCORHYNCHUS GORBUSCHA)

	Impact
Native area coastal northern Pacific ↓ **Alien area** Russia, Norway, Finland, Sweden, Iceland, Kingdom of Denmark (Greenland), Canada	Competes with native salmon; Reduces water quality; Provides an alternative fishing target

Introduction: Intentionally introduced for fishing in White and Barents Seas since 1950's, spread to other parts of the Arctic

RAINBOW SMELT
(OSMERUS MORDAX)

	Impact
Native area north Atlantic coast of North America ↓ **Alien area** Canada (Hudson Bay)	Negative impacts on native fish through competition and predation

Introduction: Spread through a combination of human introductions and secondary spread

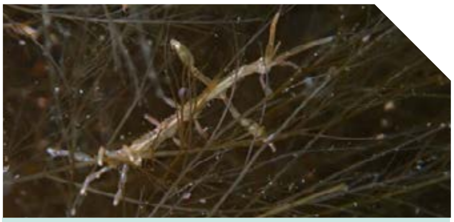
SIBLING VOLE
(MICROTUS LEVIS)

	Impact
Native area continental Eurasia ↓ **Alien area** Norway (Svalbard)	Host for the tapeworm *Echinococcus multilocularis*, which can be transmitted to humans and cause a fatal disease

Introduction: Accidental introduction with hay shipments in mid 1900's

PHOTOS: PINK SALMON: PANU ORELL, RAINBOW SMELT: KIMBERLY HOWLAND, SIBLING VOLE: TETERIA SONNNA, CC-BY, INATURALIST

EXAMPLES OF INVASIVE INVERTEBRATES



JAPANESE SKELETON SHRIMP
(CAPRELLA MUTICA)

	Impact
Native area Northwest Pacific ↓ **Alien area** USA (Alaska)	Ecological impacts largely unknown

Introduction: Introduction via hull fouling, ballast water or aquaculture. First found in early 2000's

ATLANTIC ROCK CRAB
(CANCER IRRORATUS)

	Impact
Native area east coast of North America ↓ **Alien area** Iceland	Outcompetes native species

Introduction: Accidental introduction, first found in 2006

NEW ZEALAND FLATWORM
(ARTHURDENDYUS TRIANGULATUS)

	Impact
Native area New Zealand ↓ **Alien area** Kingdom of Denmark (Faroe Islands)	Reduces the diversity and number of native species

Introduction: Introduced to Northern Ireland in 1960's, possibly through trade of ornamental plants. Found in Faroe Islands since 1982.

PHOTOS: MARINE AMPHIOID: HUNTEREFS, CC-BY-NC, INATURALIST, ATLANTIC ROCK CRAB: LEÏLA BRUNNER, CC-BY, INATURALIST, NEW ZEALAND FLATWORM: JOSHUA CLARKE, CC-BY-NC, INATURALIST

ARCTIC ECOSYSTEMS IN THE FACE OF CHANGE

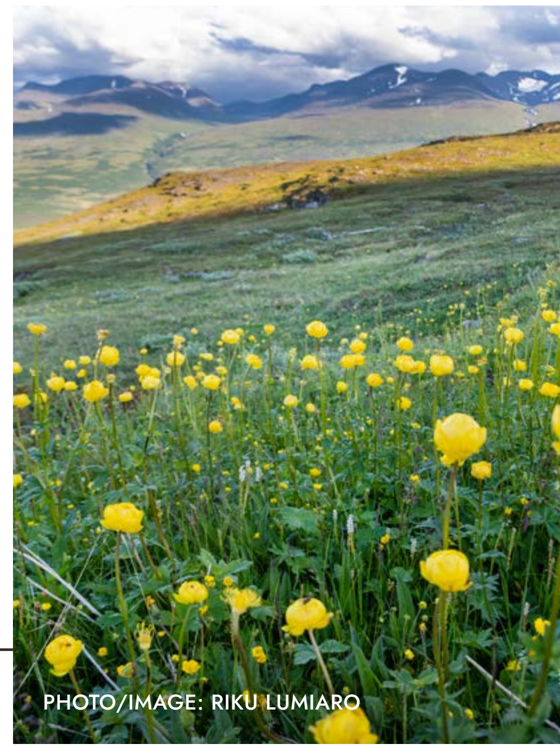
PHOTO/IMAGE: RIKU LUMIARO

The Arctic is home to many species and unique habitats that are likely to be especially vulnerable to the negative impacts of invasive alien species[3,14]. A low number of species at some levels of the food web and the prevalence of natural disturbances - factors that are generally known to make ecosystems susceptible to biological invasions - characterize many Arctic ecosystems[3,4]. Species that have adapted to Arctic conditions through life-history characteristics such as slow growth and delayed maturity may be poor competitors against invasive alien species. Furthermore, natural as well as anthropogenic disturbance regimes are shifting with increases in natural fire frequency, thawing permafrost, and increased traffic and tourism in Arctic areas[9].

CLIMATE CHANGE

The Arctic region has already been severely impacted by the ongoing climate change. Temperatures in the Arctic increased nearly four times faster than the global average from 1979 to 2021[15]. Snow cover extent has declined by 21% and sea-ice extent and thickness by 43%[9]. Permafrost thaw is occurring across the region[9]. The warming climate will facilitate the establishment of invasive alien species directly and through its effects on other drivers of biological invasions (land/sea use change, resource extraction, development)[3,9,16]. Furthermore, the combined effects of climate change and invasive alien species on biodiversity and ecosystem function can be particularly severe[14].

Climate change is already driving changes in arctic terrestrial, coastal, and marine ecosystems[9]. Milder temperatures and the reduction in ice cover favor northward expansion of Sub-Arctic species and render the region hospitable to both native species shifting their ranges northwards and alien species[14,17]. Increases in the total number of established alien species will increase the likelihood that some will become invasive[3,9,17]. Extreme events such as heat waves, rapid sea-ice loss, wildfires, and flooding, all of which can promote the establishment of invasive alien species that typically benefit from ecosystem disturbance[17], will become more frequent with climate change[4,9]. Climate change is also likely to increase the disease risk from invasive alien species through increased transmission and survival of pathogens[10].



PHOTO/IMAGE: RIKU LUMIARO

OTHER HUMAN-CAUSED DRIVERS

Human activities drive biological invasions[4]. Climate change is already increasing transport, development, and tourism in the Arctic region, and causing changes in land and sea use[3,9,18]. Anthropogenic factors that increase the risk of biological invasions rarely act in isolation, and the potentially many interactions between factors may lead to unpredicted invasion scenarios[17]. Sociocultural values, attitudes, and traditions can influence the decision-making process regarding invasive alien species, and therefore indirectly affect the outcome of invasions[19].

EXAMPLES OF DIRECT HUMAN-CAUSED DRIVERS OF BIOLOGICAL INVASIONS IN THE ARCTIC

Maritime traffic

The opportunities for maritime traffic across the Arctic are increasing as sea ice retreats[12,16]. Between 2013 and 2022 the distance sailed by ships within the Polar Code Area doubled[20], with commercial bulk carriers showing the greatest overall increase over this period. The growing maritime traffic across the region and related transport activities, both in ports and on land (e.g., railways, roads), provide important pathways for alien species introductions[17]. In particular, vectors associated with ships (ballast water discharge and biofouling of vessel surfaces) are the primary source of aquatic introductions globally as well as in the Arctic[22].

Tourism

Both marine- and land-based tourism in the Arctic have increased dramatically over the last two decades[9]. Tourism and outdoor recreation involve the movement of people, gear, vehicles, and vessels between areas, which may facilitate the movement of species and create pathways for initial introduction and secondary spread of invasive alien species[23].

Biofouling: The process by which microorganisms, plants, algae, and animals build-up on structures that are exposed to an aquatic environment, like a vessel's hull or fishing gear.

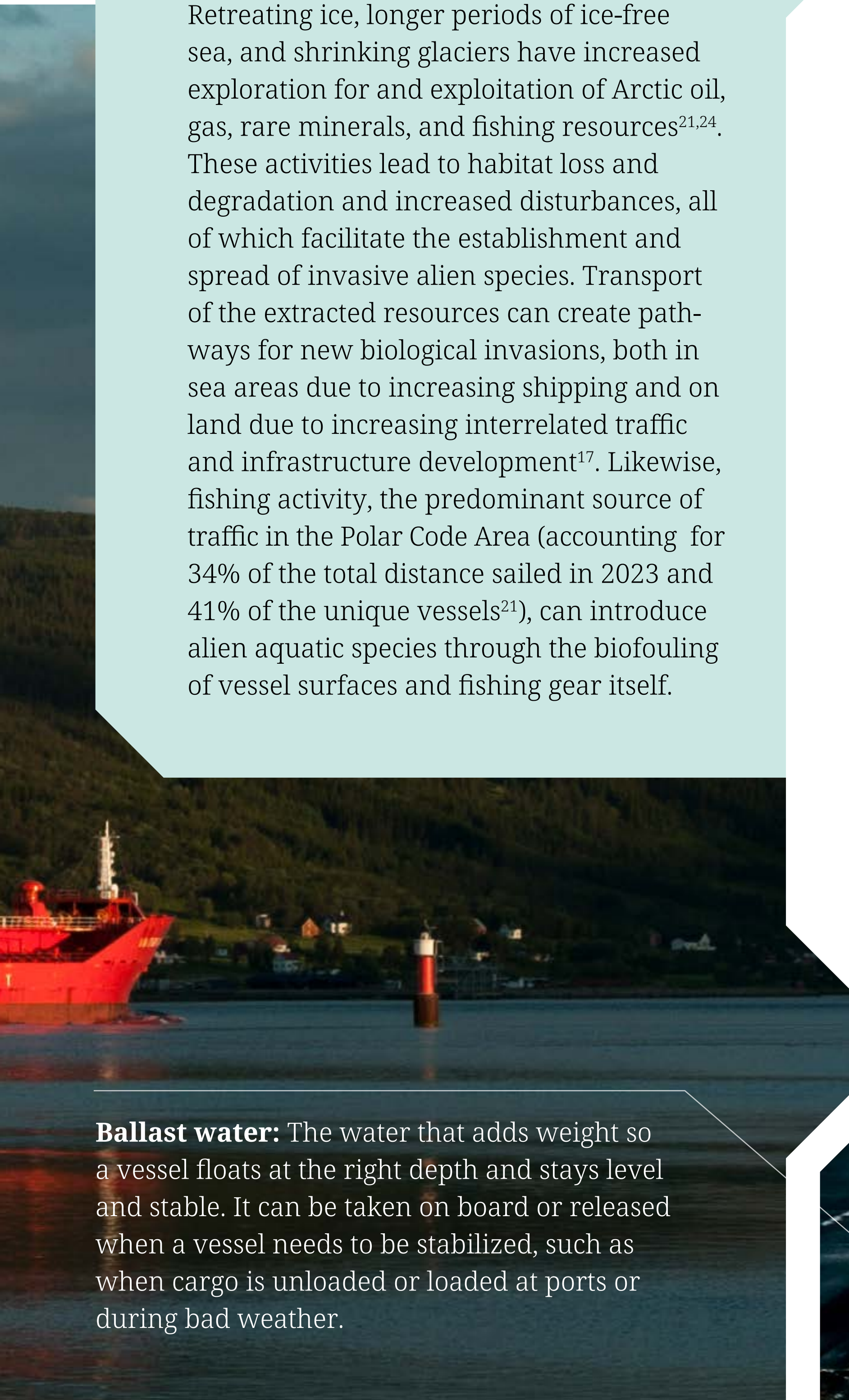
PHOTO/IMAGE: RIKU LUMIARO

Resource exploration and extraction

Retreating ice, longer periods of ice-free sea, and shrinking glaciers have increased exploration for and exploitation of Arctic oil, gas, rare minerals, and fishing resources[21,24]. These activities lead to habitat loss and degradation and increased disturbances, all of which facilitate the establishment and spread of invasive alien species. Transport of the extracted resources can create pathways for new biological invasions, both in sea areas due to increasing shipping and on land due to increasing interrelated traffic and infrastructure development[17]. Likewise, fishing activity, the predominant source of traffic in the Polar Code Area (accounting for 34% of the total distance sailed in 2023 and 41% of the unique vessels[21]), can introduce alien aquatic species through the biofouling of vessel surfaces and fishing gear itself.

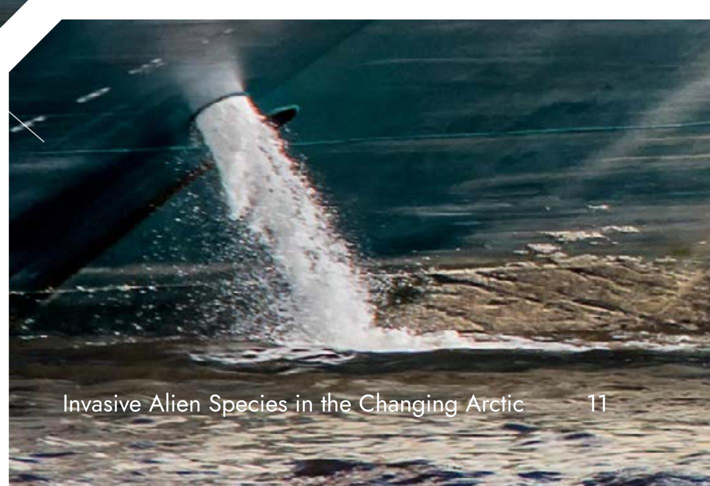
Marine debris

The issues surrounding marine debris as a pathway for invasive species are complex and not well understood. Given what we know of the increasing amount of debris in the ocean, paired with confirmed reports that organisms from distant shores (some known invaders) have been found attached to or associated with marine debris, there is mounting concern over the increasing potential for debris to assist in the spread of non-native species[25]. With a sparse human population relative to other coastal regions, the vast stretches of coastline surrounding the Arctic are especially vulnerable to invasion-vector marine debris washing ashore undetected, which creates an unfortunate framework for the unchecked spread of invasive alien species.



Ballast water: The water that adds weight so a vessel floats at the right depth and stays level and stable. It can be taken on board or released when a vessel needs to be stabilized, such as when cargo is unloaded or loaded at ports or during bad weather.

PHOTO/IMAGE: MADSCINBCA / ADOBE STOCK



MANAGING THE RISK OF BIOLOGICAL INVASIONS

PHOTO/IMAGE: RIKU LUMIARO

The process of biological invasion consists of a series of stages that describe how a native species may first become an alien species when individuals are introduced to a new location through human activities[19,26]. These alien species can then potentially turn into invasive alien species through population establishment, spread, and negative impacts[19,26] (BOX 2). Throughout this process the species must overcome various barriers that can stop the transition between stages, including geographic, survival, reproductive, and environmental barriers[19]. Introduction pathways are the means by which species overcome the geographical barriers to invasion, such as by escape or release, via corridors, or as contaminants or stowaways[27]. In many cases there is a considerable lag time from first introduction and establishment to causing harm and becoming invasive, which means that observation of current status can lead to underestimation of future threats[4].

Generally, management measures are more effective when targeted at the earlier stages of invasion (prevention)[4]. However, there are options for management at all stages of invasion[28]. Understanding the process of biological invasion is key to planning actions and interventions suitable for various invasion scenarios. For example, awareness of the relevant introduction pathways can allow identification and targeted monitoring of invasion "hotspots" where invasive alien species are likely to (re)occur[19].

BOX 2

STAGES OF INVASION

TRANSPORT

Human activities move a species, intentionally or unintentionally, through introduction pathways beyond the barriers that define its natural range.

INTRODUCTION

Species arrives at a new location outside of its natural range through human activities.

ESTABLISHMENT

Production of a viable, self-sustaining population.

SPREAD

Dispersal and/or movement in a new region or range.

ALIEN SPECIES → INVASIVE ALIEN SPECIES

MANAGEMENT INTERVENTION OPTIONS

PREVENTION of introduction between regions: international agreements (ballast water, biofouling), border biosecurity, quarantine, public awareness

ADAPTIVE MANAGEMENT: collaborative and interdisciplinary approaches to mitigate impacts

EARLY DETECTION AND ERADICATION within a geographic area: prediction of hotspots for introductions, surveillance (ports, heavily trafficked areas, offshore infrastructure), public awareness and citizen science, physical and chemical eradication, supporting healthy ecosystems

CONTAINMENT to prevent secondary spread: removal of biofouling, presence surveys, public awareness

INCREASING COSTS

REDUCED COST-EFFECTIVENESS OF MANAGEMENT

INCREASED AREA AFFECTED

ADDRESSING THE RISK THROUGH MANAGEMENT ACTIONS

The Arctic region is at a unique juncture where more invasive alien species are anticipated, and yet significant prevention of the predicted negative impacts is achievable if decisive actions are taken[3]. Prevention and preparedness are often the best and most cost-effective management options because they can limit the number of introduced alien individuals, stopping the problem at its root[4]. The success of prevention measures can be undermined by lack of capacity and funding, technical and legislative challenges, and limited infrastructure[28]. Early detection, eradication and containment can be effective as well, and can benefit from targeted efforts in disturbed and highly trafficked sites[4,29]. On the downside, eradication attempts are costly, and more likely to succeed when invaded areas are small and contained[28]. Simultaneous adoption of multiple methods, sustained resources, and communication will improve the outcomes of management of biological invasions[4].

Management of biological invasions ideally involves cooperation among Indigenous Peoples, governments, and stakeholders such as local communties at regional, national, and international scales[4]. For example, ballast water and biofouling prevention mechanisms are most effective when implemented on a global scale[30] and regional pathways for the local spread of established invasive alien species are also addressed[31]. An equally important aspect of prevention and preparedness is recognition and awareness of the rights and Knowledge of Indigenous Peoples, and local knowledge[4]. Knowledge of the current status of native, alien and invasive alien species in the Arctic would provide an invaluable baseline to help understand the predicted changes[14]. Collaborations could, for example, support Arctic taxonomic research and capacity building in the scientific community, and incorporate environmental DNA for species identification. Engaging Indigenous Peoples as well as local communities through communication about the problem and the provision of tools for reporting invasive alien species observations would afford an opportunity for both the Knowledge of Indigenous Peoples and local knowledge to be heard and provide valuable data to enable effective responses to biological invasions[32]. The inclusion of the Knowledge of Indigenous Peoples, local knowledge, and scientific expertise with community support is key to successful invasive alien species management[33].


PHOTO/IMAGE: ROBERT BAHN / UNSPLASH

BOX 3

Potential tools for sharing invasive alien species observations in the Arctic:

- Canada »
- Sweden »
- Finland »
- USA aquatic »
- Norway »
- USA general »
- SIKU - Platform by and for Indigenous communities for sharing environmental observations »

Global:

- Local Environmental Observer Network (LEO) »
- iNaturalist »

PHOTO/IMAGE: OKNETOK/ FREEPIK

CASE STUDIES

CASE STUDY 1:

INTRODUCTION AND ESTABLISHMENT OF INVASIVE PINK SALMON

The pink salmon (*Oncorhynchus gorbuscha*) is native to Northern Pacific and Russian Arctic waters, with its historic range spanning the west coast of North America, from California to Alaska, across to Japan, Korea, and east of the Lena River in Siberia. The pink salmon has a 2-year life cycle, which is shorter than many other species of salmon, and it is the fastest growing of the Pacific salmon species. Additionally, they spawn closer to tidal waters and have shorter freshwater residency than their counterparts, and, unusually for salmon, are known to occasionally spawn in rivers other than the one they were born in. This flexibility has facilitated their rapid invasion across the Atlantic over the last 10 years from an intentionally introduced and now self-sustaining population in Northwest Russia[34].

Since 2013, pink salmon have increasingly been found in rivers across Greenland and many European countries[35,36], and since 2017, Norway and northern Finland have experienced a dramatic increase in the establishment of spawning pink salmon[36-38] and successful spawning has also been observed in Iceland and Scotland[39,40]. Since 2017, pink salmon are also occasionally found on the east coast of Canada[41,42].

The establishment of pink salmon beyond their historic range has raised concerns among both industry and Indigenous Peoples. The understanding of the interactions between the invasive alien pink salmon and native Atlantic salmonids in rivers is still limited, yet there is significant potential for negative impacts through displacement of native salmonids, the spreading of novel diseases, and adverse effects on water quality[37,38,43]. While pink salmon are native to parts of Inuit homelands (the area spanning Chukotka and Alaska), they have been recorded in recent years at the mouth of the only known Atlantic salmon spawning grounds on the west coast of Greenland[35], raising concerns among community members about competition with the preferred native

PHOTO/IMAGE: PANU ORELL

Atlantic salmon. In Norway and Finland, the Saami people have discussed the rapid establishment of the pink salmon in great depth[44]. The problem is complex; on the one hand, both the invasive alien species as well as the associated eradication measures, if not selected carefully, may pose a threat to human and Indigenous rights[45], while on the other hand, the pink salmon may become an alternative catch for subsistence fishermen, thereby reducing the effects of declining native salmon stocks on Indigenous Peoples' ways of life[8].

PHOTO/IMAGE: RIKU LUMIARO

CASE STUDY 2:

COMMUNITY-BASED MONITORING AND CITIZEN SCIENCE IN EARLY DETECTION OF INVASIVE ALIEN SPECIES

An important component of early detection of shifts in species composition, including introductions of new species (invasive alien species or natural range expansions), is the establishment of programs for regular standardized monitoring. CAFF's Circumpolar Biodiversity Monitoring Program is working towards coordinating monitoring across the Arctic's major ecosystems, including the marine and coastal environment[46]. However, this is challenging in the Arctic due to its size and the limited access to many areas. Given the travel costs and logistics of sampling in many Arctic regions, the most efficient approach to regular monitoring at high-risk sites, such as shipping ports, involves development of user-friendly, standardized

PHOTO/IMAGE: CHRIS MCKINDSEY

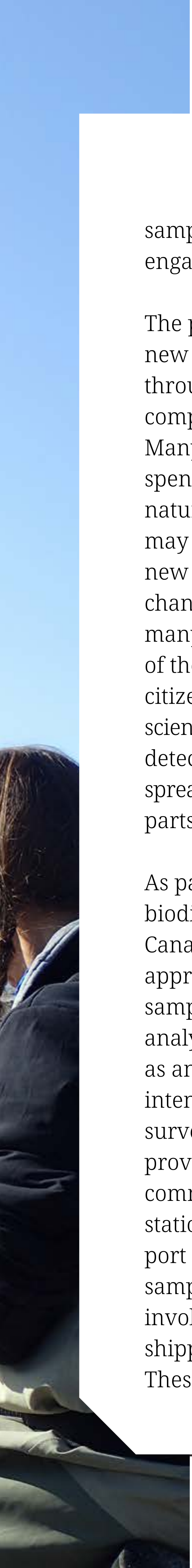
sampling approaches and training/engagement at the community level.

The probability of early detection of new species can be further increased through citizen-science, which is an ideal complement to standardized monitoring. Many citizens in the northern regions spend a considerable amount of time in nature hunting, fishing, and hiking and may therefore be the first to observe new and unusual species as well as other changes in the environment. Indeed, many aquatic alien species in other parts of the globe were first detected by local citizens, and research has shown that citizen science can be an effective approach to early detection and monitoring of alien species spread[47,48]. Resources for reporting in various parts of the Arctic are detailed in Box 3.

As part of research on baseline coastal biodiversity in high-risk ports of the Canadian Arctic, user-friendly sampling approaches including collection of water samples for environmental DNA (eDNA) analysis are being tested and developed as an alternative to more logistically intensive approaches involving dive-based surveys[49,50]. Efforts are also being made to provide hands-on training for Indigenous community members and permanently stationed northern research staff in basic port survey collection methods and eDNA sampling techniques, and to directly involve communities with relatively high shipping activity in research activities[51]. These efforts have been combined with youth-focused educational workshops to raise awareness as well as the creation of identification guides and hands-on training on how to report new sightings and distinguish potential invasive alien species from similar native species. More recently, this has been extended to include training for Inuit youth from Pond Inlet (Mittimatalik) and Igloolik communities in methods for shipboard sampling to monitor the biological risks of ballast water release in Arctic Canada's largest port on northern Baffin Island. This training is intended

PHOTO/IMAGE: KIMBERLY HOWLAND

to facilitate the development of long-term collaborations with northern communities and a larger, more cost-effective community-based network for future port and ship-based invasive alien species and biodiversity monitoring.



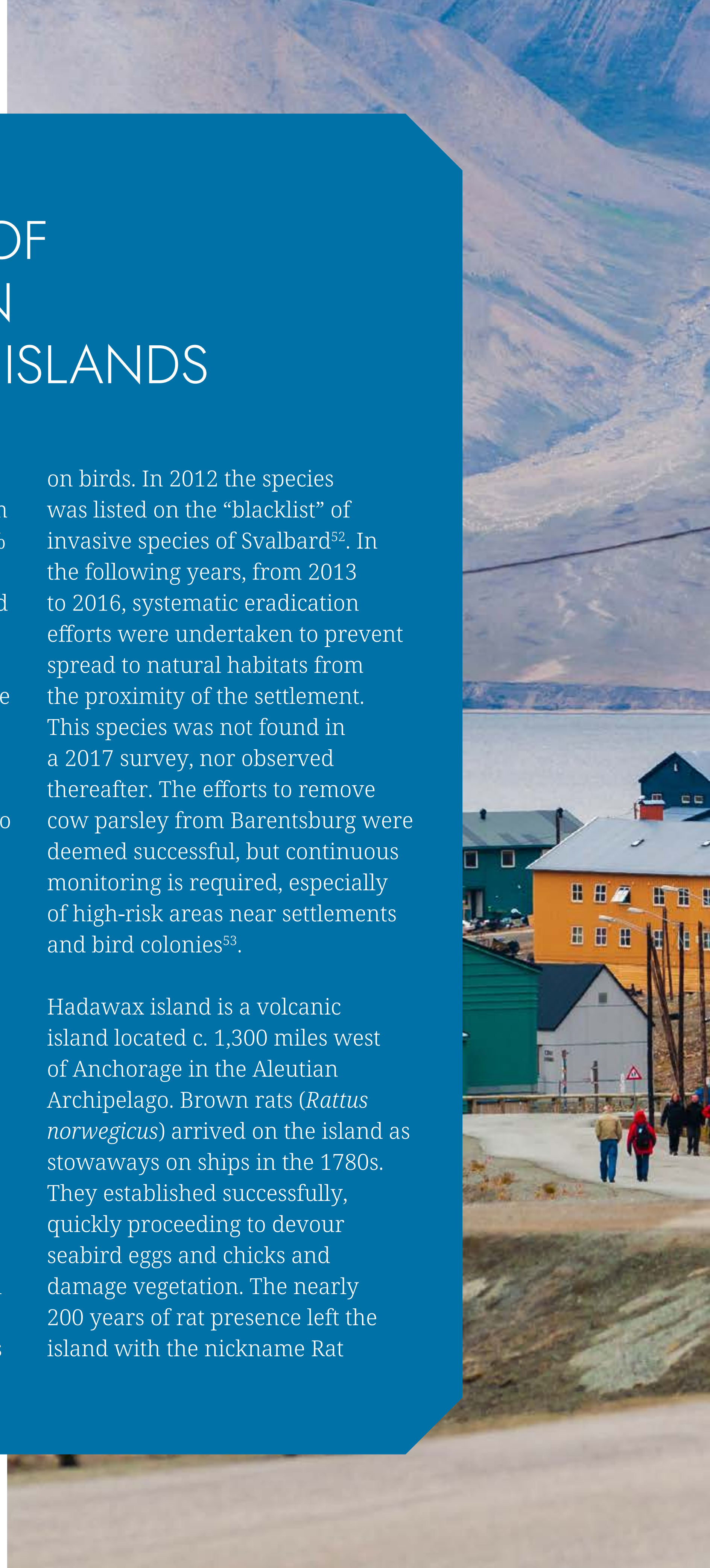
CASE STUDY 3:

ERADICATION OF INVASIVE ALIEN SPECIES FROM ISLANDS

Island ecosystems can be especially susceptible to negative impacts from invasive alien species. Globally, 90% of documented extinctions due to invasive alien species have occurred on islands[4]. Despite the often dire consequences of invasion, many eradication attempts on islands have proven to be both successful and cost-effective[28].

Svalbard is a Norwegian archipelago that lies north of mainland Europe, roughly midway between the coast of mainland Norway and the North Pole. Cow parsley (*Anthriscus sylvestris*), a species known to be invasive in other parts of the Arctic, had established near the settlement of Barentsburg in 2007. Cow parsley outcompetes other species on the bird cliffs of the Norwegian mainland and the same was predicted to occur on Svalbard. It is also able to provide better camouflage for the Arctic fox (*Vulpes lagopus*) in comparison with native plants, which was suspected to cause cascading negative impacts on birds. In 2012 the species was listed on the "blacklist" of invasive species of Svalbard[52]. In the following years, from 2013 to 2016, systematic eradication efforts were undertaken to prevent spread to natural habitats from the proximity of the settlement. This species was not found in a 2017 survey, nor observed thereafter. The efforts to remove cow parsley from Barentsburg were deemed successful, but continuous monitoring is required, especially of high-risk areas near settlements and bird colonies[53].

Hadawax island is a volcanic island located c. 1,300 miles west of Anchorage in the Aleutian Archipelago. Brown rats (*Rattus norwegicus*) arrived on the island as stowaways on ships in the 1780s. They established successfully, quickly proceeding to devour seabird eggs and chicks and damage vegetation. The nearly 200 years of rat presence left the island with the nickname Rat



Island. In 2008, the U.S Fish and Wildlife Service, in partnership with two NGOs (Island Conservation and the Nature Conservancy), successfully eradicated the rats by spreading cereal grain pellets containing rodenticide. Within five years of the eradication, the numbers of birds increased and nesting success improved. Important locally extinct bird species, among them the Aleutian endemic giant song sparrow (*Melospiza melodia maxima*), recolonized the island[54]. After 11 years, the ecological community once again resembled a rat-free island, with significant decreases in intertidal invertebrate species abundances and increases in fleshy algal cover[55]. The project partners continue to work together to prevent the reintroduction of invasive rats to the island[3].

PHOTO/IMAGE: DON LANDWEHRLE / ADOBE STOCK

CASE STUDY 4:

INVASIVE SPECIES BROUGHT TO THE ARCTIC BY MARITIME TRAFFIC

In terms of Arctic marine species, ships are the most prevalent vectors in marine systems, through organism entrainment in ballast water and biofouling[22,56]. An analysis of current trends and future invasion risks in the large marine ecosystems of the Arctic shows that ships transfer the greatest number of aquatic non-native marine organisms (39%) to the Arctic, followed by natural spread (30%) and aquaculture activities (25%)[57]. In the case of maritime traffic, pelagic crab larvae and

PHOTO/IMAGE: GUENTERGUNI / ISTOCK

eggs transferred by ballast water and biofouling on ship hulls are assessed as high risk for Greenland Arctic waters[58]. Highlighting the importance of shipping in relation to other marine aquatic invasion pathways, there have been no documented species introductions from aquaculture activities in U.S. coastal waters or EEZs to the Arctic.

To minimize the risk of introducing aquatic invasive alien species by ballast water, the International Maritime Organization (IMO) adopted the International Ballast Water Management Convention[59]. The Convention requires ships which take up ballast water during international voyages to manage their ballast water to minimize the risk of transfer of alien species into coastal areas, typically through the use of approved filtration and disinfection systems.

Studies of polar maritime traffic have demonstrated that biofouling on the external hulls and ballast tanks of vessels operating in ice-covered waters can support a wide variety of non-native marine organisms[57,60–62]. The IMO has developed non-binding Biofouling Guidelines to encourage the control and management of ships' biofouling to minimize the transfer of invasive aquatic species[63]. In addition, some nations impose biosecurity measures such as biofouling compliance regulations for incoming vessels[64,65].

Implementation of regulations regarding the treatment and handling of ballast water and control of biofouling on ships, whether for national or international traffic, is of crucial importance to reduce the likelihood of transfer and spread of alien species to Arctic waters.

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