3. Melting Sea Ice, Accelerated Shipping, and Arctic Invasions

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3.1 Introduction

Although ships have plied the world's ocean for centuries, polar waters have been significantly less connected by maritime trade than most other parts of the globe. This is especially true of the waters of the Arctic, where, until recently, extensive sea ice has precluded access throughout most of human history. While Nordic mariners and indigenous peoples have long inhabited and traversed coastal arctic waters, their vessels were neither as large, moved as fast, nor traveled as far as the modern ships of today. Under the growing influence of global climate change, shipping in arctic waters is undergoing a dramatic increase as the reduction in sea ice cover is opening the region to commercial navigation and exploitation of natural resources, in particular, petroleum and mineral extraction, and arctic fisheries (Ruiz and Hewitt 2009, Arctic Council 2009, Christiansen *et al*. 2014). It is not yet clear what impacts such human activities will have on the Arctic's ecosystems; however, the opportunity for biological invasions by marine organisms is certain to increase. The loss of sea ice is opening the Arctic to commercial shipping for several months per year (NSRIO 2014). New and expanded shipping activities in arctic waters under global warming create a new corridor for efficient global transport of commercial goods, but in so doing, inadvertently create a corridor for the inter-ocean transport of marine species in the ballast water and on the hulls of ships moving between the Atlantic and Pacific. These activities are expected to introduce potentially harmful non-native species to the Arctic as well as to enhance the introduction of non-native species across oceans and port systems at lower latitudes.

This chapter explores the role of shipping as it relates to the movement and introduction of marine species beyond their natural ranges, with particular focus given to shipping in arctic waters. Beginning with a short primer on marine invasion biology, this chapter then explores ships as non-native species vectors (i.e., via ballast water and hull fouling), highlighting expected changes to shipping in the Arctic. These processes are placed in the context of global climate change and the expectation of accelerating rates of shipping as they relate to a) shorter transport distances and times between oceans and b) the growing exploitation of arctic natural resources that rely heavily on shipping. Finally, a brief summary of the current international regulatory framework related to ships as vectors of non-native species (i.e., ballast water and sediments and to biofouling of ships' hulls) and a call for immediate consideration of vector management approaches are presented.

3.2 Marine Invasions

Once introduced to a region outside its biogeographical range, a species might fail immediately, persist without attaining a self-sustaining population, or develop a sustaining population that persists for some period of time. A self-sustaining population is the hallmark of a successful biological invader; however, depending on the extent of impact that a non-native species has on the receiving habitat and environment (e.g., superior competitor, predator, or habitat engineer), a species may be considered "invasive". In general, invasive species are considered those that cause extreme ecological or economic damages, or that pose threats to human health. Three classic examples of truly invasive species that were likely introduced by commercial shipping are the zebra mussel *(Dreissena polymorpha)* invasion of the Great Lakes and fresh waterways of the United States; the comb jelly *(Mnemiopsis leidyi)* invasions of the Black and Caspian Seas; and the Northern Pacific seastar *(Asterias amurensis)* invasion of Australia.

Following introduction, there are two major factors that influence invasion success; that is, whether a species is able to survive, reproduce, and importantly, develop a self-sustaining population. The first is related to a species' physiological tolerance of a new environment. In the case of marine and estuarine species, environmental factors such as water temperature, salinity, and wave energy (e.g., open or sheltered coastline) have been shown to be important for shaping invasion success and failure, as has access to appropriate physical habitat. Thus, there needs to be a certain degree of match between a species' physiological tolerance and the environmental conditions of the non-native setting if an invasion is going to succeed. To some extent, an environmental match among native and introduced ranges can provide some insight into the likelihood of invasion success; however, environmental matching is a far from perfect predictor of invasion success.

A second factor is the biological resistance generated by native communities to would-be invaders, which can affect the vulnerability of a system to invasion. Once introduced, will a non-native species be able to gain access to sufficient food and shelter to generate a self-sustaining population, or will native species' competitive and predatory abilities be so great that the invader is precluded? Biological resistance to invasion is among the least well understood and difficult to predict aspects of invasion biology.

The availability of suitable habitat types for non-native species is essential for invasions to succeed. In the United States and elsewhere, marine invaders are most common in estuaries and other coastal embayments, often colonizing man-made habitats (pier pilings, coastal hardening structures, etc.; Ruiz *et al*. 2000a, Dumont *et al*. 2011).

The underlying reasons for enhanced invasion success in these settings are not fully understood, but may be related to a variety of conditions. For example, the common positioning of ports in sheltered embayments means increased propagule supply from shipping in an environment that typically has lower wave energy and lower rates of physical flushing, characteristics that can better retain propagules compared with open coast habitats where propagules may be dispersed rapidly. Propagule retention may increase encounter rates by mates, thereby increasing chances for successful reproduction (Floerl and Inglis 2003). Furthermore, port development alters the natural habitat significantly, including substantial additions of hard substrate, a habitat requirement of many invertebrate species that can be carried in ballast water or on the hulls of ships. Anthropogenic habitats have been shown to enhance colonization by non-native species as providers of novel habitats and potential refuges from native predators, thus significantly altering local ecological communities (Glasby *et al*. 2007, Bulleri and Chapman 2010, Dumont *et al*. 2011). Habitat disturbance associated with coastal development can also perturb the ecological integrity of native biological communities, including, as many believe, their ability to repel invasions by non-natives (Elton 1958, Byers 2002, Valentine and Johnson 2003).

3.3 Commercial Ships as Vectors

Commercial ships are widely recognized as vectors by which biological organisms can move, albeit inadvertently, across oceans and beyond the bounds and barriers of their natural distributions (Carlton 1985, Ruiz *et al*. 2000a, Fofonoff *et al*. 2003, Hewitt *et al*. 2009). The vast majority (>90%) of global cargo moves by commercial ships, providing extensive opportunity for the translocation of biota (Minchin 2006).

3.3.1 Ballast Water

Ships provide at least two significant mechanisms for the transport of non-native species. The first is ballast water, water that is taken into specialized ballast tanks or cargo holds in order to stabilize empty or partially loaded ships in various sea states and weather conditions. Ballast water also ensures proper trim and steering of the vessel. Ballast water, and its associated sediments, are typically taken aboard and discharged in connection with the off- and on-loading of a ship's cargo, meaning that most ballasting operations occur in ports and coastal waters. Importantly, in addition to the water itself, the biota suspended in the water column (e.g., zooplankton, phytoplankton, larval stages of invertebrates and fishes, as well as bacteria and viruses) are entrained with the water and deposited in ships' ballast tanks (Carlton 1985, Carlton and Geller 1993, NRC 1996, Ruiz *et al*. 2000b). Those ballast water inhabitants that do not expire inside a tank during transit can be discharged into ports as cargo is taken aboard the ship.

3.3.2 Hull Biofouling

A second important ship-related invasion vector for biological transport is on the exterior surfaces of ships' hulls where organisms cling. So-called "biofouling" or "hull fouling" (Godwin and Eldredge 2001, Gollasch 2002, Hewitt *et al*. 2009) occurs on the wetted hull surfaces of ships as well as in and around specialized niche areas such as sea chests, bow thrusters, propellers, anchors and chains, and untreated dry docking support surfaces (Coutts and Taylor 2004, Inglis *et al*. 2010). Biofouling can consist of microorganisms that begin developing biofilms within hours of a hull making contact with water to more complex communities of sessile macrofauna and flora (e.g., barnacles, sponges, sea squirts, mussels, algae) that accumulate over weeks to years. In fact, niche areas, especially those that are removed from the shear forces created by water moving by the hull, can harbour mobile organisms like crabs or seastars. In a broad range of geographic locations, hull fouling appears to be as important and sometimes more important than ballast water as an invasion vector for non native species (Cranfield *et al*. 1998, Fofonoff *et al*. 2003, Hewitt *et al*. 2004, Davidson *et al*. 2009, Ruiz *et al*. 2011, pers. comm. Davidson IC).

Hull biofouling is not new, historically wooden hulled vessels were plagued by boring shipworms, which could compromise the mechanical integrity of the hull (Carlton 2001), but other species were also moved on these hulls. Prior to the 1880s, when the first steel hulled vessels were developed, wooden hulls were sometimes clad with copper or other substances to reduce biofouling (Hewitt *et al*. 2009). Modern steel hulled vessels are immune from the kinds of damage faced by wooden ships, however, the biofouling of hulls can induce significant drag on a moving ship which results in lower fuel efficiency, adding substantially to operating costs (Minchin 2006). To combat hull fouling and corrosion, the shipping industry has developed antifouling coatings that contain a variety of biocidal agents that kill or repel biofouling (e.g., copper and now banned tributyl tin (TBT)) or substances that make the hull surface slippery so that organisms are unable to cling or remain attached, especially as a ship moves through the water a particular speeds and for lengths of time (see Chambers 2006 for in depth description of antifouling agents and approaches). Due to negative environmental impacts from TBT and related organotins on natural marine communities, these widely used (and very effective) antifouling agents were outlawed internationally as an ingredient in antifouling paints in 2003 under the International Maritime Organization's International Convention on the Control of Harmful AntiFouling Systems on Ships (AFS 2001). In the absence of antifouling compounds of similar or greater efficacy, both Nehring (2001) and Hewitt *et al*. (2009) have suggested that the discontinuation of organotin may actually result in an increased risk of hull fouling invasions worldwide.

Both the ballast water and hull fouling vectors move living biota in vast numbers and over significant distances, often introducing them widely to regions well outside their native geographic distributions (Carlton 2001, Ruiz *et al*. 2000a, Fofonoff *et al*. 2003). The relative lack of shipping activity in arctic waters has meant that these high-latitude regions have experienced little in the way of non-native species propagule pressure (Ruiz and Hewitt 2009, Ware *et al*. 2014). Here propagules are considered organisms of various life stages, be they adults, juveniles, larvae, or cysts/resting stages. Propagule pressure is composed of two components, 1) the number of propagules introduced, and 2) the frequency of inoculation events. Propagule pressure has been shown to strongly influence the likelihood of invasion success (Lockwood *et al*. 2005, Verling *et al*. 2005, Johnston *et al*. 2009). Yet there remains significant uncertainty as to the exact relationship between propagule pressure and a quantifiable risk of invasion (Minton *et al*. 2005, NRC 2011). Nevertheless, despite scientific uncertainty surrounding this relationship, there is broad agreement that reductions in propagule pressure should lead to significantly lowered risk of invasion (Verling *et al*. 2005, NRC 2011).

3.4 Arctic and Trans-Arctic shipping

Maritime activities in the Arctic, both historic and contemporary, are no doubt complex and driven by the interests of multiple nations, both inside and outside the Arctic region (see Arctic Council 2009, Zellen (ed.) 2013 for recent treatments of this subject.) Although there are many drivers affecting polar shipping, the perceived economic benefits from the exploitation of natural resources (both living and non-living) and the use of arctic waters as a shipping corridor to further connect economies of the Atlantic and Pacific appear paramount, but safe passage through icy arctic waters will remain challenging (Arctic Council 2009, Lawson 2013). An international research team lead by the United States Geological Survey has estimated that approximately 13% of the world's conventional oil (~90 billion barrels) and 30% of the world's natural gas (~1.67 trillion ft^3) may occur north of the Arctic circle, with the majority of gas to be found in Russia (Gautier *et al*. 2009). High latitude oil exploration and extraction have taken place in the Arctic for over 5 decades, but as global warming reduces the extent of sea ice coverage, accessibility is expanding rapidly and technical obstacles are falling away. Geopolitical considerations and impediments to petroleum and mineral extraction have also played important roles in the tempo of these activities.

With the recent signing and ratification (2010 and 2011 respectively) of the Maritime Delimitation and Cooperation in the Barents Sea and the Arctic Ocean treaty between Norway and Russia, a territorial dispute that strongly limited shipping and undersea petroleum exploration for decades was resolved. This treaty opened up approximately 175,000 km^2 of the Barents Sea and Arctic Ocean to oil and gas exploration (Amos 2011), a region suspected rich in petroleum reserves. Importantly, the agreement between Norway and Russia has cleared the way politically for commercial ships carrying commodities and tourists, as well as fishing vessels, to pass through and use these waters without fear of legal retribution.

3.4.1 Northern Sea Route and Destination Voyages

The Russian Federation established the Northern Sea Route Administration, a body that issues permits, regulates and assists commercial vessels passing the approximately 3,000 miles along the Siberian peninsula from west to east (from Barents Sea to Bering Straits) and east to west (NSRA 2014). The Northern Sea Route (NSR) represents a new seasonal shipping corridor for commercial ships moving between Europe and Asia, as well as among ports and places along the route; for example moving liquid natural gas from Russia to Europe or Russia to China. The first commercial bulk carrier ships navigated the NSR in 2009 (Evers 2013) and in 2010, the Norwegian Tschudi Shipping Company in cooperation with other shipping companies pioneered some of the first non-Russian shipping across the NSR from Europe to China (TGSC 2010). Since 2009, the number of ships making passage has increased significantly to 71 transits, carrying 1.29 million tons of cargo during the 2013 shipping season. Additionally, over 350 permits were issued in 2013 for ships to operate inside the Northern Sea Route (NSRIO 2014).

Table 1 summarizes some of the apparent economic incentives and disincentives for using this new inter-oceanic corridor.

Table 1: Examples of economic incentives and disincentives to Arctic transits via the Northern Sea Route

Incentives	Disincentives
Fuel savings	Reinforced hulls
Time savings	Passage fees
Draft restrictions/ DWT limitations	Icebreaker escorts
Piracy reduction	Seasonality

In addition to growing use by ships transiting from Europe to Asia and vice versa in arctic waters, the number of destination voyages (i.e., ships that travel into polar waters for specific operations such as petroleum exploration, exportation of liquefied natural gas at LNG terminals, tourist visits by passenger vessels, and commercial fishing) are expected to far outstrip transits (Lawson 2013).

The economic drivers of both NSR transits and destination voyages in the Arctic appear enormous, but the environmental costs of such activities, including those of marine invasions, although less easily monetized, should be considered carefully as we expand our considerable and likely irreversible influences in the Arctic. Deliberations must be multinational, including indigenous peoples, and should occur in a variety of policy and regulatory fora (e.g., the Arctic Council, United Nations' International Maritime Organization (IMO)).

3.4.2 Polar Code

The Polar Code, an international agreement of the International Maritime Organization (IMO) is designed to develop and codify specific international rules and regulations for ship safety and construction in the Arctic and Antarctic. Pending finalization, the Polar Code is expected to enter into force in 2016 (IMO 2014, Koranyi 2014). Importantly, the Polar Code sets forth operational safety measures and rescue regulations for ships operating in high latitude waters, as well as certain environmental and pollution prevention protections to reduce risks of oil/chemical spills. However, the Polar Code is silent on issues of invasive species that are associated with ballast water discharge and hull fouling of ships and other maritime structures such as mobile offshore drilling platforms.

All vessel operations in the arctic region pose potential risks for the introduction or regional dispersal of non-native hull fouling species. Invasion opportunity is also present for those vessels that discharge ballast water, with those ships that do not follow any sort of ballast water management or treatment posing the greatest risk. Tanker vessels that export Russian and Norwegian liquefied natural gas (LNG) will be continual and repeated sources of large volumes of foreign sourced ballast water from the geographic regions of their customers (e.g., European countries in the Atlantic and Asian countries in the Pacific). Likewise, the hulls of these same ships will generate large fluxes of wetted surface area with significant potential for biofouling. Dedicated routes for specialized products like LNG may pose particularly great risks for marine invasions, since the likelihood of repeated introductions of large numbers of propagules is high. In the case of Arctic LNG, large new terminals are being planned with the expectation of serving both Europe and Asia (e.g., in Sabetta, Russia; Evers 2013). Nevertheless, this situation also provides a unique opportunity for the consideration of land-based or nearshore ballast water reception/treatment facilities, an invasion prevention solution that is not suitable in most ports, but which may be economically feasible if originally designed as part of a specialized LNG terminal.

3.5 Climate Change

Arctic land and sea surface temperature are warming at faster rates than other parts of the globe; permafrost, snow cover, and sea ice are retreating, trends that are expected to increase in the coming century (IPCC 2013). These changes to the environment will increase human activities in the Arctic considerably. For example, increased shipping and changing trade patterns, petroleum and mineral exploration, extraction and export, coastal and port development, tourism, fishing (both harvest of natural stocks and increased aquaculture), and anthropogenic debris are each expected to result in greater opportunity for invasions in the Arctic (Ruiz and Hewitt 2009). In fact, shipping will underpin all of these activities. Therefore, when increased propagule pressure from shipping traffic is combined with habitat disturbance and alteration, and changes in sea ice cover, water temperature, sea level rise, and salinity, it is reasonable to assume that the rate of non-native propagule transport to the Arctic is likely to increase.

3.5.1 Migration and Natural Dispersal

A study by Vermeij (1991) documented natural migrations of molluscs that occurred during the Pliocene epoch, the last period when the Arctic is known to have been ice-free (5.3 to 1.8 million years before present). Migrations were strongly asymmetrical, with 261 species moving from the North Pacific to North Atlantic, and just 34 species moving in the opposite direction. Vermeij attributes this pattern to strong prevailing currents that moved northward through the Bering Strait and hypothesizes that a lack of sea ice enabled phytoplankton concentrations to increase via warmer temperatures and increased light penetration/photosynthesis, which in turn fueled migrations. Recurrence of an ice-free Arctic will no doubt support natural dispersal and migration, but will concomitantly enhance environmental conditions for transport and post-arrival survival of biota moved by humans.

The discovery of a North Pacific diatom species (*Neodenticula seminae)* in the Laborador Sea in 1999 by Reid *et al*. (2007) indicates that the reduction of arctic sea ice has influenced water circulation current patterns, enabling a species that has not occurred in the North Atlantic for 800,000 years to migrate between oceans. The authors discuss ballast water as a possible vector for the diatom, but conclude that given the small number of ships and volume of ballast water moving between the two regions in the late 1990s, ballast water was an unlikely vector. With shipping in the Northern Sea Route on the rise and the transit of the first commercial coal carrier through the Northwest Passage in 2013 (McGarrity and Gloystein 2013), active shipping and ship vectors (ballast water and biofouling of hulls) in the Arctic, and connecting the Pacific and Atlantic will surely increase propagule pressure and invasion opportunity.

3.5.2 *Modeling and Experimental Approaches to Invasion and Invasibility*

Given the diversity of biota and vectors in play, predicting the next important invasive species is impossible. However, examining the physiological capacity to withstand environments beyond current geographic distributions can provide insight. Using a niche modeling approach that incorporates a suite of environmental parameters reflective of current species' distributions (MaxEnt, see Elith *et al*. 2011), deRivera *et al*. (2011) modeled the capacity for several marine invaders (e.g., crab, barnacle, tunicate, snail) of the Pacific coast of North America to tolerate higher latitude regions of Alaska under projected environmental scenarios of 21st century conditions (IPCC 2007). These models predicted that changing climate in Alaska would create environmental conditions tolerable to the species studied. When model projections were expanded globally for year 2100 IPCC projections, most of the species were shown to have physiological capacity to withstand future conditions in some parts of the Arctic (B. Steves and C. deRivera, unpublished data).

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) estimated the risk for invasions to Svalbard. Their modeling suggested that in the second half of 21st century, Svalbard will be increasingly vulnerable to invasion as a function of climate change and increased propagule pressure from ships.

Beyond theoretical modeling approaches, experimental methods can be applied to test various aspects of invasion biology. Experiments that test physiological tolerance of biota are common in many areas of study (e.g., toxicology/ecotoxicology). Agricultural sciences have long sought to understand how to optimize growth and production of crops, but have also invested extensively in the study and application of biological control of invasive species. Likewise, ecologists have used field experiments extensively to understand community assembly rules and the drivers of biodiversity, including invasion dynamics (e.g., Sousa 1979, Stachowicz 1999). Marine invasion biologists are increasingly using laboratory and field experiments to understand various aspects of marine invasions such as the role of propagule pressure on invasion success (e.g., Clark and Johnston 2005). Using field experiments, Crooks *et al*. (2011) tested the differential effects of copper on naturally occurring assemblies of native and non-native species in San Francisco Bay. The investigators found that native diversity was reduced significantly more than non-native diversity, when exposed periodically to a copper solution. To understand the survivorship/mortality of would be invaders, researchers from the Smithsonian Environmental Research Center are using an experimental test platform to simulate ship voyages that apply actual shipping route conditions, a method they are now applying to possible biofoulers of commercial ships that transit the Arctic (GM Ruiz, personal communication).

To most rapidly advance our understanding of arctic invasions, it is incumbent that investigators employ all methodologies at hand, with a goal toward educating managers and policy-makers about what can be expected and what might be done to reduce the number and ameliorate the impacts of marine invaders.

3.6 Ocean acidification

An additional driver of global change is the acidification of oceanic waters due to increasing carbon dioxide (CO_2) concentrations. As CO_2 increases in the atmosphere, the surface waters of the ocean absorb significant portions (>25%), driving the system toward an air-sea equilibrium (Sabine *et al*. 2004, Royal Society 2005). In seawater, higher CO_2 results in lower pH (more acid) and a lowered bioavailabilty of carbonate ions for the biogenic generation of calcium carbonate, the building block of calcareous biota (Orr *et al*. 2005). Water that is high in CO_2 will be reduced or even under-saturated with respect to aragonite and calcite, two mineral forms of calcium carbonate used by many calcareous organisms to generate hard body parts. Because cold waters are able to absorb CO_2 more readily than warm waters, the chemistry of acidification in high-latitude ocean regions is expected to be more accentuated than in temperate and tropical regions (Fabry *et al*. 2009).

To date, investigators have shown a variety of biological responses to ocean acidification and discovered that not all taxa respond similarly, even demonstrating species-specific responses among closely related biota (see Doney *et al*. 2009 for review of ocean acidification and biological responses to it). A recent meta-anlaysis of five important animal taxa (corals, echinoderms [starfish and sea urchins], molluscs [bivalves, snails], crustaceans [crabs, shrimp, barnacles, and fishes) indicated differential responses to elevated CO_2 (Wittman and Pörtner 2013). The corals, echinoderms, molluscs, and larval fishes appear to be more sensitive to elevated concentrations of CO_2 (i.e., 936 ppm in year 2100 projected under the IPCC's RCP8.5 scenario) than do crustaceans, generally showing diminished performance and deleterious effects in calcification, growth, metabolic processes, and behavior. Elevated CO_2 and reduced pH has dramatic effects on certain species of pteropods, free swimming pelagic snails that build aragonite shell structures (i.e., dissolution of shells within hours of exposure to conditions projected for the 21st century; Orr *et al*. 2005, Fabry *et al*. 2009). Pteropods occur at high densities and have been shown to be very important prey to juvenile pink salmon, (>60% by weight, Armstrong *et al*. 2005). Phytoplankton too show variable responses, both among calcifying (e.g., cocolithophores) and non-calcifying species. Recent mesocosm studies carried out off the coast of Svalbard, Norway indicate that the smaller phytoplankton (nano and picoplankton) thrive under high CO_2, but that larger phytoplankton suffer due to strongly reduced levels of essential nutrients, suggesting important foodweb and biogeochemical effects from acidification (Riebesell *et al*. 2013). Fabry and colleagues (2009) review the effects of ocean acidification at high latitudes on both ocean chemistry and biotic responses, and recommend that polar waters be viewed as bellwethers for the rest of the globe.

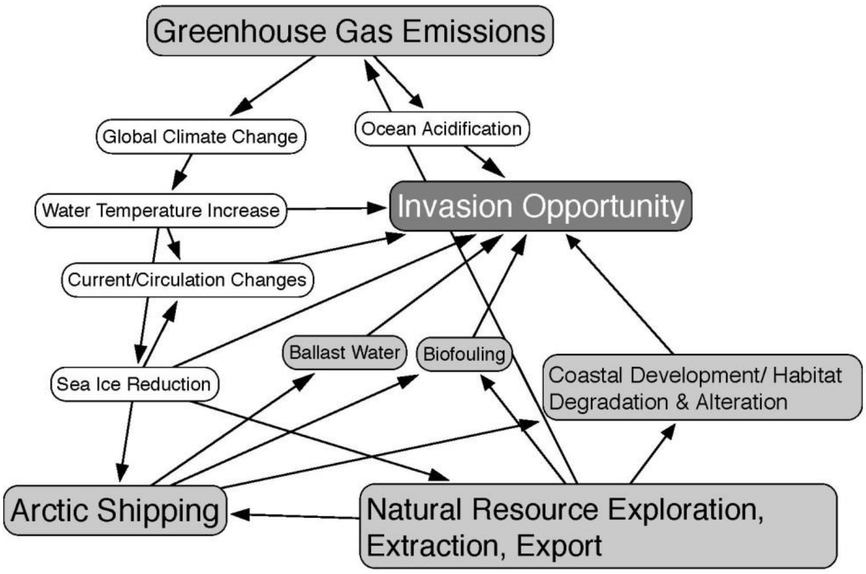
At present, it is still too early to predict the ecological-scale effects of acidification in arctic waters; however, given the mounting evidence of negative biological effects on species that reside in the water column and benthos, changes to arctic ecology may alter community structure and function, thereby changing the biological resistance to non-native species. A growing number of studies performed near natural volcanic underwater CO_2 seeps indicate strong effects on community assembly and diversity of benthic biota (Hall-Spencer *et al*. 2008, Kroeker *et al*. 2011), further suggesting that opportunities for invasion by non-native species will likely change in a high-CO_2 world.

3.7 Drivers and Determinants of Invasion Opportunity and their Interactions

Human induced global climate change, caused in part by the increased extraction and burning of fossil fuels, is rapidly influencing both the physical and biological realms of the Arctic region (IPCC 2007, 2013). Among the most important changes are increasing ocean temperatures and the loss of sea ice coverage in polar waters. These and other environmental changes may have direct effects on ecological communities of the Arctic, which in turn may influence their vulnerability to marine invasions. Such changes are already having direct effects on the number of commercial ships operating in the Arctic, and are expected to factor in greatly to the extent of natural resource exploration, extraction, and export that take place in the Arctic. Climate-induced shifts in shipping patterns and natural resource exploitation of the Arctic will alter the landscape and seascape in many ways that will influence invasion opportunity (Ruiz and Hewitt 2009).

Figure X.1 is a concept diagram summarizing how anthropogenic greenhouse gas emissions influence climate change and ocean acidification processes, thereby affecting the opportunity for Arctic invasions both directly and indirectly, through other human-mediated activities. While not comprehensive, the diagram is meant to be illustrative of some important interaction of environmental change, human behavior, and arctic invasions. For example, shipping directly affects the volume of ballast water delivered, but shipping activities are directly influenced by sea ice coverage. Rising water temperatures have direct influences on invasion opportunities as well as direct effects on currents and patterns of ocean circulation, which themselves will also affect dispersal of both native and non-native species. Natural resource extraction will enhance greenhouse emissions (the fundamental driver of all the pictured interactions), but will also strongly influence shipping, coastal development/habitat degradation, each of which will affect invasionopportunity.

Figure X.1: Concept diagram



Concept diagram relating invasion opportunity to anthropogenic greenhouse gas emissions, global climate change, ocean acidification, arctic shipping/vectors, and natural resource exploration/extraction. Arrows indicate directionality of effect, but not strength of interactions. Environmental effects of to greenhouse gas emissions are depicted in white, human activities in light grey, and invasion opportunity in dark grey.

3.8 Ship Vector Regulations

Although various countries have developed legally enforceable statutes and regulations for ballast water management (e.g., Australia, Canada, New Zealand, and the United States), the primary international effort to reduce risks of marine invasions is the IMO's International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) which was adopted in 2004. However, not until 12 months after 30+ maritime countries, representing 35% of the global shipping merchant tonnage, ratify the convention can it enter into force as an international treaty (Albert *et al*. 2013). Although the IMO began seeking international protections against ballast water-borne invasions in the 1980s (Hewitt *et al*. 2009), it was not until 2004 that numerical discharge standards were considered internationally (i.e., specific concentrations of viable biotic propagules of 3 size classes: >50um minimum dimension, >10um and <50um minimum dimension, and certain indicator microbes; Albert 2013). Currently, the United States via the U.S. Coast Guard and U.S. Environmental Protection Agency have assumed the BWM Convention's so-called "D-2 Ballast Water Performance Standards" as the basis for ballast water management and discharge (see Albert 2013 for a more detailed analysis of international BW regulations).

Unfortunately, the process for seeking international agreements/treaties on reducing the risk of ballast water invasions has been arduous, and despite apparent recent progress, a treaty will likely take years to fully implement since it will require the development, type approval testing, and installation of onboard ballast water treatment systems on existing ships and new builds. Until such time, many view open-ocean ballast water exchange (BWE, the process of exchanging coastal ballast water and the coastal biota it contains with pelagic water/biota, prior to discharge in subsequent ports or coastal ecosystems) as the best interim management method for reducing marine invasion risk.

It is of interest to note that as of this writing, five of eight member sates of the Arctic Council have ratified the IMO BWM Convention (Norway, Russia, Canada, and Denmark, and Sweden), but the United States, Finland, and Iceland have not. Although not a signatory, the United States' federal regulations require mandatory ballast water reporting and management of overseas ballast water and the vast majority of vessels report ballast water management of some kind, either open ocean BWE, no discharge of BW, or use of an alternative onboard BW treatment system (National Ballast Information Clearinghouse Reports to United States Coast Guard (NBIC 2014), but see Miller *et al*. 2011 for discussion of some limitations of ballast water exchange). It is encouraging that acknowledgement of marine invasion risk and ballast water management is common among Arctic nations, suggesting that international cooperation on this issue may be achievable.

Despite widespread concern for marine invasions associated with hull fouling of ships, at present, there are no international conventions or legally binding international agreements in place that address the invasion risks associated with biological fouling of ships' hulls. Rather, in an effort to heighten awareness and encourage international cooperation for reducing the risks of hull fouling, the IMO Marine Environment Protection Committee has drafted international guidelines for effective antifouling systems, suggested hull husbandry and dry-docking schedules, as well as biofouling management (IMO 2011). Some countries (e.g., Australia, Canada, New Zealand), as well as individual states in the U.S. (Hawaii and California) have put fairly stringent regulations into force, which in some cases require underwater inspections of a ship's hull prior to port entry. Floerl (2014, this volume) describes the broader principles, with examples, of how biofouling management is being connected with risk assement as a means for reducing marine invasions.

3.9 Vector Management

The uncertainty associated with invasion prediction speaks to the complex nature of the invasion process. Indeed, there are many opportunities and reasons for invasion failures. As described above, invasion success requires the development of a self-sustaining population once introduced beyond the native range. However, there are many potential filters that can result in invasion failure, even prior to the introduction of non-native propagules. Although ships are important vectors for many marine and estuarine species, there are many other vectors by which species are moved around the world. For example, aquaculture, the aquarium trade, live seafood, and bait trade are examples of important vectors by which biota are transported from one location to another. Indeed, even individual species can be moved and introduced by multiple vectors (Ruiz *et al*. 2011, Williams *et al*. 2013), suggesting that coordinated management of vectors, rather than species-specific approaches to invasive species management, will be the most effective approach for reducing marine invasions.

Whatever the vector, an animal, plant, or protozoan must 1) be entrained alive (e.g., into a ballast tank or to the hull or niche space on a ship's hull), 2) survive the physical and chemical rigors associated with transport in the vector (e.g., hull foulers must withstand temperature, salinity, food availability, shear stresses, and possible toxicity associated with antifouling paints and coatings), and 3) be introduced to a new environment alive. Once introduced, an organism must then at minimum meet the environmental and biological challenges of the new setting in order to survive and successfully reproduce, if an invasion is to be possible. Each of these junctures in the invasion pathway represents an opportunity to reduce in number or eliminate viable biota being entrained, transported, and introduced to new habitats, including newly accessible regions of the Arctic. Floerl (this volume) describes how risk assessment and other approaches can help with understanding and managing invasion risks associated with ships.

3.10 Conclusions

With arctic shipping, exploitation of natural resources, and coastal development all increasing, it seems both urgent and prudent for the international community (the Arctic nations especially) to seek cooperative approaches and agreements for reducing and managing the invasion risks associated with biofouling, ballast water, and other possible vectors of marine species. Employing vector management, rather than species by species approaches, will be the most effective and efficient method for invasion prevention. The vector approach is a philosophy that has guided management and policy of ballast water for over 20 years. As a vector, biofouling of hulls presents additional challenges, and treatment technologies, management approaches, and regulations/law are badly needed. In the face of global climate change, researchers must concentrate their efforts on a fuller understanding of the make-up, structure, and function of "natural" arctic marine ecosystems, as best they can. That said, rather that waiting for a full scientific accounting, we must look to other global regions for lessons on invasion impacts and for insights into how these impacts might be prevented. Whether we choose an "Arctic Manifest Destiny", whereby our drive for expanded economies far outstrips our desire to conserve and protect the Arctic's unique environment, or instead seek the possibility of more sustainable Arctic development, is an open question.

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