Increased prevalence of human activity in the Arctic as a result of climate change, and the impacts on the Arctic ecosystem from resulting increases of introduced species

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Abstract

Arctic sea ice levels have been steadily decreasing since the end of the 20th century, and there is no evidence of this trend disappearing in the coming years. As a result of this, shipping routes are opening up within Arctic seas, and ships have begun traversing through these waters with increasing consistency. These ships are bringing with them countless hull fouling organisms and ballast waters filled with invasive species. With increasingly temperate conditions in the Arctic, the ecosystem is becoming more and more susceptible to adverse effects of invasive species. This paper discusses specific invasive species in the Arctic, the impacts that these organisms may have on the carefully balanced Arctic ecosystem, and policies that may help combat the adverse effects of a steadily increasing prevalence of invasive species within the area.

Introduction

Indigenous Peoples have lived in the Arctic for over 6000 years (Raghavan et al. 2014). However, throughout this time, these peoples known as the Inuit, Athabascan, Saami, and many more, have lived sustainable lives. They have practiced hunting and fishing, although only in numbers great enough to feed their families and communities (Simon 2011). For this reason, it can be said that human activity in the Arctic has remained relatively low throughout the years. In the context of the paper, human activity will be described as increased uses of shipping routes, and an increasing reliance on and popularity of fishing and aquaculture, tourism, and natural resource extraction from the ecosystem.

Based on this definition, it is only within the last century that human activity has been on the rise within the Arctic, beginning with an exponentially increasing whaling industry in the 1600s (Simon 2011). Since the late 20th century, sea ice levels within the Arctic have been severely decreasing as a result of climate change (Shepherd 2016). These decreased levels of sea ice are leading to incredibly magnified probabilities of ample ships traversing Arctic waters through new passages within the next 30 years, a stark difference to the sustainable lifestyles of the Indigenous peoples throughout the last six millennia (Smith et al. 2013). As sea ice levels continue to decline, one of the effects most intensely studied are the possible Arctic shipping routes being opened. Through the use of certain Arctic maritime pathways, the average time to reach Asia could decrease from a minimum of thirty days to just seventeen. This is a source of industry fascination due to the possibility of decreased shipping costs and environmental emissions (Melia et al. 2016).

Over the years, shipping has been a major global source for introduced and invasive marine species all around the globe, and will continue to be in coming years if policies are not enforced in order to combat just that (Molnar et al. 2008). As a result of an increasing shipping presence within the Arctic ecosystem, there will be an increase in invasive species introduced to Arctic waters through hull fouling and ballast water releases. These two occurrences have been identified to be the largest causes of intercontinental aquatic species exchanges (Drake et al. 2007). In the context of this paper, the term ‘invasive species’ will be used to define species not historically native to the Arctic that were brought there by aid of humans and have the possibility of establishing a successful population (Simberloff 2013).

Across the globe, invasive species have been seen to have effects such as displacing or dominating over native species, diminishing fisheries, altering food webs, and many others similar to these (Molnar et al. 2008). Although most times, introduced species cannot survive well in the new environments they are transferred into, once they become settled they can be almost impossible to remove (Thresher et al. 2004).

Historically, impacts of invasive species within Arctic ecosystems have been very low compared to temperate or tropical environments. This decreased impact was due to comparatively low prevalence of Aquatic Invasive Species (AIS) as a result of frigid water temperatures and an infrequent presence of ships attributable to high levels of sea ice and therefore inaccessibility for large ships to pass through the area. However, with global warming now leading to warmer, more temperate oceanic conditions and a drastic decrease in sea ice levels, the Arctic is now becoming more susceptible to invasive and introduced aquatic species (Chan et al. 2018). Before the year 2050, the Arctic is predicted to be seasonally ice-free (Notz et al. 2018). Before the year 2100, the mean air temperature of the Arctic is predicted to increase by 4.5 degrees Celsius, which will result in a subsequent increase in water temperatures in the area (Weslawski et al. 2011). Both of these predictions drastically increase the effects that invasive species are expected to have on the Arctic ecosystems.

Transportation of Invasive Species

Increasing numbers of Arctic sea routes are becoming available, and therefore there are increased levels of invasive species being introduced into the ecosystem through hull fouling and the release of ballast waters. Shipping is the most prominent transporting vector for aquatic invasive species around the globe. In 2003, it was determined that shipping, and the consequent occurrence of hull fouling and ballast water release, may have contributed to nearly 80% of introduced invertebrate and algal species in North America (Fofonoff et al. 2003). Additionally, trans-oceanic shipping to large ports has been linked to the introductions of a majority of non-native species (Godwin 2010). In the following section, the effects of both invasive species transportation vectors, hull fouling and ballast water release, will be discussed.

Hull fouling is the occurrence of marine life attaching to and growing on the hull of a ship. Organisms are then transported along with the ship, and can be randomly introduced to a new environment after being knocked off by a wave or losing grip and falling off. Over the years, shifts from wood hulls to steel hulls have reduced the effects and prevalence of fouling organisms, but have still not managed to eliminate them completely (Godwin 2010). For this reason, hull fouling is still a very prominent threat to the Arctic ecosystems.

In a study conducted in 1995, the effectiveness of hull fouling as way of transport for introduced species was analyzed. It was found that, compared to the organisms present at the start of the journey, there was very little loss in taxa at the conclusion of the journey, with an average of 92% surviving each of three voyages. The conclusion of this study was that hull fouling is an important and note-worthy source for the introduction of invasive marine organisms (Carlton 1995).

However, the previous study was conducted on a ship replicated from the sixteenth century. This does not accurately portray the effects that hull fouling might have in the modern shipping world. Modern ship designs have begun to incorporate new technologies such as steel or aluminum hulls and antifouling coatings as an attempt to decrease the effects and likelihood of historical levels of hull fouling (Godwin 2010, Chambers et al. 2006). These attempts will be further discussed in the Policies section of the paper.

The releasing of ballast water is the other widely studied way that invasive species are being introduced to Arctic waters. Ballast water is taken into and released from a vessel at varying times in order to decrease stress on the hull, provide better maneuverability, reduce vibrations and unplanned movements, and many other things. Most times, ballast water is taken in and released at ports, as this is the time when the cargo of the ship changes and the difference needs to be balanced. This exchange leads to many microorganisms being accidentally transported from port to port, and results in the introduction of invasive species to new ecosystems (Government 2010). Currently, nearly 80 million tons of foreign ballast water are received by the United States in one year, each of which contains nearly one billion bacteria and over seven billion particles similar to viruses (Ruiz 2000). In future years, it is estimated that around 5% of the world's trade could be shipped through the Northern Sea Route if sea ice was not a limiting factor (Yumashev 2017). Arctic waters are predicted to be seasonally ice free within the next 30 years, and an annually ice-free Arctic will likely not be long to follow. This would then lead to an incredibly increased use of the Northern Sea Route as a shipping pathway, and it becomes clear that this extreme loss of ice in the Arctic will actually be introducing massive amounts of new organisms to the ecosystems by way of ballast water release.

In a study conducted in 1988, ballast waters transferred between Japan and Australia were collected and analyzed over the course of 2 years. Several species of nekton, and hundreds of species of plankton were found to be contained in these waters. A large majority of the organisms were benthic, which is likely due to the intake of sediment along with ballast waters in ports containing shallow or turbid waters. The results of this study suggest that ballast-tank sediment is just as important in the transport of nonnative species as the ballast water itself. It was also concluded that increasing shipping speeds are increasing the likelihood of organisms surviving the journey in the ballast tank and being released in a new environment, healthy and ready to reproduce. In historical times, ships traveled at much slower rates, and it is likely that the species they were carrying had died before reaching the final destination. This would have decreased the effects of ballast water exchange, and can be used to explain why current shipping rates and speeds are such a concern regarding the inevitable spread of invasive species (Williams et al. 1988).

In another study conducted, levels of planktonic life were measured before, during, and after ships' journeys, and it was determined that although planktonic life decreased over the course of the trip, a substantial amount was still transported alive to the ending location. This proves ballast water release to be an important and note-worthy way of transport for invasive species (Lavoie et al. 1999). Increased amounts of ships in the Arctic will ultimately result in more ballast water releases into the ecosystem, and therefore radically amplified introduction rates of invasive and nonnative aquatic species.

Invasive species present in the Arctic

Several studies have been conducted to analyze invasive species transported into the Arctic ecosystem through hull fouling and ballast waters. In a scientific paper evaluating the risks of invasive species introduced to Svalbard through ballast waters and hull fouling, it was found that threats will be begin to be posed to the ports of the country in the year 2050. After that year, it is likely that the waters of 2 ports in Svalbard will closely match the waters of frequent source ports of ballast waters released in Svalbard (Ware et al. 2014). Source ports are the ports from which ships travel and collect ballast water in. The decreasing difference between the waters of the identified source ports and the waters of Svalbard suggests that introduced species will be better equipped to establish populations in Svalbard's waters than in previous years. This will facilitate the rapid spread of introduced species within the country's waters, as a result of rising water temperatures that are not predicted to cease increasing.

In the Canadian Arctic, eight invasive species were identified as high risk to the area based on the likelihood of being transported to ports through ballast water or biofouling, and the probability that the species would be able to survive in the increasingly more moderate oceanic conditions. Three of the eight high-risk invasive species, which included the Periwinkle (*Littorina littorea*), the Soft-shell clam (*Mya arenaria)*, and the Red King Crab (*Paralithodes camtschaticus)*, were all considered to be current threats to the Canadian Arctic based on environmental conditions. However, with continually increasing prevalence of ships and warming waters within the area, it is predicted that all eight high-risk species will prove to present a tremendous threat to the ecosystem within the century (Goldsmit et al. 2018).

The largest prevalence of introduced species in the region has been identified in sub-Arctic Icelandic waters. Over 14 nonnative species have been identified in the area, and of these species, 4 have been identified as potentially invasive. These include *Fucus serratus*, a species of Macroalgae, *Cancer irroratus* and *Crangon crangon*, species of Crustacea, and *Platichthys flesus*, a species of fish (Thorarinsdottir 2014). The introduction of the European Brown Shrimp (*Crangon cragon*) is attributed to repeated releases of contaminated ships' ballast water releases, as well as natural introduction through currents. Since it was first identified in the area in 2003, the species has spread through the West and South coasts of Iceland and is predicted to continue spreading as ocean temperatures warm and create an increasingly temperate environment in which the species can thrive (Chan et al. 2018). *Fucus serratus* was likely introduced to the area in the 1800s, and has since spread to the Faroe Islands and become well-established within several fjords (Coyer et al. 2006). *Cancer irroratus*, the Atlantic rock crab, is believed to have been introduced to the sub-Arctic as larvae transported in ballast waters. The species has currently colonized over 20% of Iceland's coast, and is only expected to increase that number in the coming years, due to the lack of natural predators or competitors within Icelandic waters, and the noticeably warming aquatic temperatures. The species is native to the Atlantic coast of North America, and will likely thrive in the ever-warming waters of the sub-Arctic, and eventually Arctic, region. Lastly, *Platichthys flesus*, the European Flounder, was first identified in Icelandic waters in the year 1999, and has already increased its distribution to nearly the entirety of the country's circumference. The introduction of this species is unknown, although is suspected to once again be through ballast water releases of ships (Thorarinsdottir 2014).

With the increasingly temperature conditions within the Arctic, it is likely that the 4 potentially invasive species currently colonizing sub-Arctic Iceland will expand their range into the Arctic circle within the years to come. This range shift could be expected to have an extremely large impact within marine Arctic ecosystems.

Effects on the Arctic Marine Ecosystem

Introduced invasive species can be the cause of local extinctions, resource competition, disease transmission, and many other negative effects within an ecosystem (Thorarinsdottir 2014). Additionally, adverse effects within fisheries economies in the Arctic resulting from introduced invasive species can cause economic problems within countries and Indigenous communities.

Within Icelandic waters, the high genetic diversity, abundance, size, and reproductive success of the introduced species *Cancer irroratus*, or the Atlantic rock crab, provide evidence that the organism has successfully colonized the area. This crab maintains an opportunistic and generalist diet of mainly native benthic species, and does not face competition with its natural adversary in Iceland, the American lobster (*Homarus americanus*). The species' effect on benthic species is thought to increase in coming years, due to the magnitude of an individual crab's diet, and the observed lack of natural predators (Gíslason et al. 2014). Without competition for resources with the American lobster or any other organisms, the *Cancer irroratus* population is likely to grow exponentially as a result of seemingly unlimited resources and the absence of any obvious limiting factors. Without a presence of limiting factors, effects on benthic communities are unlikely to remain small. Increasing prevalence and success of the species in Icelandic waters will presumably cause trophic imbalances as a result of consuming food sources of other previously established species in the area, such as Haddock (*Melanogrammus aegelfinus*), Atlantic wolffish (*Anarhichas lupus*), and Long rough dab (*Hippoglossoides platessoides*) (Jaworski et al. 2006). All of these species have been observed to maintain a heavily benthic diet within Icelandic waters, and the increasing success of *Cancer irroratus* would directly diminish food sources for these organisms, resulting in the displacement or possible local extinctions of these 4 species of fish.

Another example of adverse effects of these invasive species within Icelandic waters can be seen in the establishment of the European flounder, *Platichthys flesus*. This species has been observed to prey on other fish species' larvae, and compete for food and spatial resources with Atlantic salmon (*Salmo salar*), European eel (*Anguilla anguilla*), and Threespine stickleback (*Gasterosteus aculeatus*) (Thorarinsdottir 2014). Although the European flounder feed on a variety of organisms, but the majority of their energy intake is from benthic-dwelling mollusks, shrimps, and small fish (Skerrit 2010). Increasing prevalence of *Platichthys flesus* in the waters surrounding Iceland can be predicted to result in decreasing prevalence and success of Atlantic salmon, European eel, and Threespine stickleback as a result of resource competition within the ecosystem. This can be predicted to result in additional observances of localized extinctions and displacement of these native species.

As a result of warming waters and increasingly more temperate conditions within the Arctic circle, species have begun to expand their range into the continental shelves of Arctic waters. Species that have expanded their sub-Arctic range into the Arctic within the near past include, but are not limited to, the Atlantic snake pipefish *Entelurus aequoreus* and the Fourhorn sculpin *Myoxocephalus quadricornis* (Fleischer et al. 2007, Dyck et al. 2007).

In a study conducted in the year 2007, the Atlantic snake pipefish, a species historically found near the South of Iceland, was identified off the coast of Svalbard. It was determined that this finding was evidence for the previously predicted northward range expansion of the species. Although the ecological effects are currently understudied, it is believed that an increased presence of these organisms will result in predation pressure to zooplankton residing in Arctic waters, particularly those surrounding Svalbard (Fleischer et al. 2007). The evidence of this species expanding its range northward of Icelandic waters provides evidence and support for the likelihood of species such as the Atlantic rock crab or the European flounder, mentioned earlier, to also expand their ranges into Arctic waters.

Another example of range shifting can be most heavily identified through the Fourhorn sculpin's relationship with the Black Guillemots, *Cepphus grille mandtii,* of Cooper Island. From the year 1975, when the colonies were first studied, to the year 2003, this species of bird has fed primarily on Arctic Cod. However, from 2003 to 2012, nearly 30% of the birds began consuming sculpin, as opposed to historical rates of less than 10%. This range shift has yielded negative effects on the Black Guillemot population, such as decreased levels of reproductive and fledging success. This can be attributed to a lower nutritional value of the fish and an increased difficulty of digestion (Divoky et al. 2015).

The observed range shifts of the Arctic cod and Fourhorn sculpin within the Arctic seas provide evidence for the possibilities of invasive species currently residing in the sub-Arctic to shift into the Arctic as waters warm. There will not only be most favorable conditions for these organisms to thrive in, but opportunities for introduction will drastically increase as a result of increased shipping rates.

As a result of more and more range shifts occurring from sub-Arctic to Arctic waters, the largest concern then becomes that the organisms currently wreaking havoc off the coast of Iceland will soon adopt the same strategy and begin to integrate themselves into the Arctic ecosystem. The Arctic ecosystem and food webs are highly benthic-oriented, and the presence of invasive organisms such as the European flounder and the Atlantic rock crab will likely result in severe trophic imbalances across the entirety of the Arctic, and a drastic shift in the current food web as a result of their impacts on benthic communities (Renaud et al. 2010). The range shifts of Arctic cod and sculpin have had severe negative effects on the Black Guillemot population on Cooper Island, and it is likely that the introduction of previously mentioned invasive species into Arctic ecosystems will cause similar although unpredictable effects on species yet unknown.

Although uncertain, the effects of invasive species entering the Arctic environment will presumably cause large shifts in food webs and trophic relations, markedly those connected to the benthos. These shifts will have a substantial effect on economies in the Arctic, most notably those of small Indigenous Arctic communities. Many villages, such as those of the Inuit peoples, rely heavily on subsistence hunts and the selling of traditional clothing made from pelts of these hunted animals as a majority of the community income (Freeman et al. 2006). Predicted shifts in food webs and trophic relations will affect the quantity and quality of animals hunted, resulting in a poorer hunting, and therefore community, economy. This heavy reliance on the current equilibrium of the Arctic marine ecosystem may prove problematic in the coming years, leading to both financial and health-related difficulties as the reliability of subsistence hunts begin to dwindle.

Policies to Decrease Introduction of Invasive Species

There have been many policies or solutions suggested to decrease the probability of transporting organisms through ballast water and hull fouling throughout the years. The most efficient, cost-effective, and convenient solutions within Arctic shipping routes will be detailed below.

As was previously stated, there has been a large shift from wood to steel or aluminum hulls in boats since the sixteenth century (Godwin 2010). However, this solution is not always completely effective, as certain organisms have still been able to attach themselves to the metal hulls and be transported to new environments by way of hull fouling. The development of antifouling coatings has proven to be an effective way to counteract this fouling. Antifouling coatings are usually in the form of organic enamels, lacquers, varnishes, primers, or others of the like. They are painted onto ships in order to prevent the attachment of various organisms and prevent the metal from corroding.

The use of antifouling coatings can have unforeseen benefits such as decreasing fuel consumption due to decreasing hydrodynamic drag created by the colonization of organisms on the hulls of ships, and increasing maneuverability by decreasing fouling on propellers or rudders. Though the use of these coatings can bring many benefits for decreasing the transportation of invasive species and decreasing use of fuel, there are several downsides as well. Historically, these coatings have been produced with copper, a metal that it relatively harmless to humans, but can have drastic effects on marine organisms, even when present in miniscule amounts. As new alternatives are being developed, the effects that these solutions will have on marine environments is daunting and unpredictable (Chambers et al. 2006).

Despite the unpredictable environmental effects of improved antifouling coatings, engineers are continually attempting to create improved versions. Once a marine ecosystem-safe formula is developed, this will most likely prove to be a large benefit for the Arctic environment. The increased shipping rates would no longer bring with them the threat of introducing thousands of non-native and possibly invasive organisms through the method of hull fouling.

Ballast water exchange (BWE) is currently the most common and reliable source of minimizing invasive species transport. The two most common techniques for conducting BWE are empty-refill or flow-through. In empty-refill, the ballast tank is reduced to less than 95% of the original volume, and then refilled with water immediately. To achieve the flow-through technique, water is simultaneously pumped into and out of the ballast tanks. Several studies have found that Ballast water exchange reduces the number of planktonic species and organisms by 80-95%, as compared to the ballast tanks of ships that partook in the same voyage but did not practice mid-ocean ballast water exchange. These techniques have also been determined to have largely decreased the transport of nonnative organisms through ballast tanks to the Great Lakes, Chesapeake Bay, and several others areas within the United States. This has, as a result, also decreased the risk of invasive species disturbing the natural ecosystems of these environments (Ruiz et al. 2007).

In the United States, ships arriving at ports are required to conduct mid-ocean ballast water exchange greater than 200 miles off shore, which has proven to be the most effective way of preventing the introduction of non-native species to coastal waters. One of the biggest problems faced in the Arctic regarding the enforcement of BWE is the proximity of designated exchange zones to coastal ecosystems in which the introduced species may become established and invasive (Jing et al. 2012). This is due to the comparatively small width and depth of the Arctic Ocean, making it difficult to reach areas deep enough and far enough from the surrounding coasts to participate in efficient and effective ballast water exchange. Additionally, the ice that remains in the Arctic contributes to the inability to distance the boats enough from the shore.

The combination of metal hulls on ships, the creation of marine-safe antifouling coatings, and the determination of efficient ballast water exchange sites within the Arctic are likely vital to the future of the Arctic marine ecosystem. Policies addressing the enforcement of all three of these things within Arctic and sub-Arctic oceans and seas would drastically reduce the probability of the introduction of invasive species into the Arctic through hull fouling and ballast water release.

Conclusion

The likelihood of invasive species being transported to Arctic marine ecosystems through ballast water release and hull fouling has drastically increased within the past few years. The introduction of nonnative species such as the soft-shell crab, the Atlantic rock crab, and the European flounder in the waters of Canada and Iceland provide evidence for what is soon to occur in the Arctic as human activity in the form of shipping increases within the area.

Global warming is the driving force behind both of these new levels of invasive species within sub-Arctic and Arctic waters. The decreasing levels of sea ice are allowing for the passage of more ships within the area, directly resulting in increasing levels of ballast water release and hull fouling organisms. Additionally, the rising water temperatures are increasing the occurrence and probability of range shifts of organisms previously only present in sub-Arctic waters. This makes the increase of invasive species in Icelandic and Canadian waters all the more worrisome, as it is likely that those organisms will also be shifting their ranges into the Arctic in the years to come. This would increase the prevalence of invasive species even further, and therefore the likelihood of a drastic change within Arctic food webs and ecosystems in the near future.

These increasing levels of introduced and invasive species might also have previously unpredictably large effects on Arctic economies. The fisheries economies of the Arctic, especially those based in Indigenous communities, are highly dependent on the current balance of species. If invasive species were to overtake Arctic waters and shift trophic relations, fishery and subsistence hunt-based economies would collapse.

Through the enforcement of policies regarding the material of ship hulls, the use of antifouling coatings on the underside of boats, and the determination of safe and effective ballast water exchange sites, the risk of invasive species introduction to Arctic waters can be immensely reduced. Similarly, if policies regarding those same priorities are enforced within the sub-Arctic, effects of range shifts from Icelandic and Canadian waters might also decrease.

Although the current invasive species situation in the Arctic may seem grim, through the creation and enforcement of policies, the prevalence of invasive species can be diminished, and the effects on Arctic ecosystems and economies subdued.

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