# Assessing the Harmful Impacts of Increased Commercial Shipping on Arctic Marine Mammals: A Systematic Literature Review

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**Abstract**

The endemic species of marine mammals that live in the Arctic year-round have been increasingly threatened by melting Arctic sea ice over the past several decades. Reduction in sea ice has led to increases in multiple commercial Arctic shipping routes, such as the Northwest Passage and the Northern Sea Route. This paper systematically reviews peer-reviewed literature to assess the impacts of melting sea ice and increased use of Arctic shipping routes on key species of Arctic marine mammals. Further, I also discuss several proposed solutions to mitigate the negative effects of these issues. I find that the most highly documented impacts of commercial shipping activity are noise pollution, oil spills, and ship strikes. Harmful effects of these activities include behavioral change, in which mammals alter their feeding, breeding, and pupping behaviors due to the presence of commercial ships, toxicological effects from ingestion of pollutants, and mortality. Multiple shipping regulations have been proposed, including altering vessel routes and reduction of ship speeds, but many studies do not analyze the potential effects of these regulations and therefore fall short of providing adequate and descriptive policy suggestions. Even though 65% of papers discuss shipping regulation in some form, only 58% propose future regulations, and 46% evaluate the effect of that regulation. While climate change is frequently mentioned in papers considering Arctic shipping, climate policy is especially neglected. This literature review reveals crucial gaps in the current body of knowledge, both in animal and ship monitoring data and policy effectiveness, and highlights important areas for future research to inform policymaking in light of climate change. Modifying and creating new policies for the mitigation of harmful shipping impacts is important for the protection of Arctic marine mammals as climate change continues to worsen.

*Keywords:* Arctic, Arctic marine mammals, shipping, sea ice, climate change, shipping impacts

## Introduction

Global climate change has caused the 2019 minimum extent of sea ice to be the second lowest in the satellite record (Overpeck et al., 1997; Cosimo, 2003; National Snow & Ice Data Center, 2020). Together sea ice declines and sea level rise are resulting in a longer "open-water" period in the Arctic, in which there is no sea ice obstructing potential shipping routes. This has consequently contributed to interest in increased use of trans-Arctic international shipping routes (Laidre et al., 2015). Further, warming in the Arctic has caused sea ice to reach a 12.85% decline per decade (National Snow & Ice Data Center, 2020). The change in the open-water period is particularly appreciable during the late summer months, where the open-water period has increased by five to ten weeks, allowing more time for vessels to transit these key waterways (Laidre et al., 2015). In fact, the Arctic Council's Protection of the Marine Environment Working Group states that the number of vessels entering the Arctic region has increased by 25% and distance traveled by vessels by 75% from 2013 to 2019, indicating a very recent significant increase in trans-Arctic ship traffic (PAME, 2020). Recent heavy use of popular routes, such as the Northwest Passage and Northern Sea Route, has increased the vulnerability of Arctic marine mammal (AMM) species to various threats caused by vessel traffic (Hauser et al., 2018). Understanding and mitigating these impacts through AMM monitoring, planning for risk avoidance to mammals, and protective legislation is important to protecting these vulnerable species.

Increased shipping poses many potential threats to AMMs, including human-generated underwater sound, ship strikes, displacement from critical habitat, and accidental or illegal oil discharge (Laidre et al., 2015). For example, ship noise can alter mammal behavior in the form of risk avoidance or cessation of foraging (Halliday et al., 2019), or lead to acoustic masking, in which animals cannot effectively hear a signal of interest, such as location of prey or communication with other animals, due to significant ambient noise (Pine et al., 2018). Despite these effects being widely recognized, the vulnerability of several AMM species has not been extensively assessed, making it difficult to accurately determine and attempt to mitigate shipping threats. Understanding the effects of shipping on these species is important due to their critical ecological roles and cultural value. AMMs serve important ecological roles as both predator and prey in Arctic marine ecosystems (Marine Mammal Commission, 2019). Indigenous peoples rely on AMMs, such as ringed and bearded seals, beluga and bowhead whales, narwhals, walruses, and polar bears, for food, clothing, and other products (Hovelsrud et al., 2008). Thus, mitigating these threats is considered urgent (Hauser et al., 2018), particularly as shipping activity continues to increase.

This thesis aims to systematically review the consequences and future implications of melting sea ice and increased use of Arctic shipping routes on AMMs, as well as determine how these consequences differ among species. Another objective is to discuss the efficacy of proposed solutions in mitigating the negative effects of increased Arctic shipping. To do so, I asked:

1) How is shipping activity impacting marine mammals?

2) What are the suggested mitigation tactics for negative impacts (e.g., legislation, ship safety regulations, monitoring)?
3) What is known about future impacts of Arctic shipping on marine mammals under climate change?

Despite the importance of increasing shipping in the Arctic and this being an active area of research, there has yet to be a systematic review that thoroughly assesses the ecological implications of increased shipping as well as the policies to combat them. There exists a previous literature review that discussed changes in Arctic shipping, but it is more focused on the economic implications of the use of shipping routes as well as environmental assessments of these routes (Theocharis et al., 2018). In this review, mammals are not discussed at all; rather, it reviews comparative studies of Arctic shipping routes and expands on economic feasibility and comparison of environmental impacts of emissions of said routes (Theocharis et al., 2018). The policy discussed in this review strictly regards environmental aspects of shipping, such as usage of certain fuel types, rather than protection of Arctic species (Theocharis et al., 2018). Conversely, in my review, I evaluated the effects of shipping on marine mammals that are most commonly addressed in literature and examined the most frequently suggested regulatory systems to address the effects of shipping on AMMs.

**Methods**

To assess the effects of increased Arctic shipping and evaluate the various strategies to mitigate the negative effects, I examined the peer-reviewed literature using the protocol for

systematic review outlined in the Collaboration for Environmental Evidence (CEE) guidelines (Collaboration for Environmental Evidence, 2013). My preliminary results included 47 publications retrieved from the Web of Science online database as of December 16, 2020. These publications were found using the search term sequence ( "arctic" and "marine" and "mammal*" and "shipping" and "impact*" ) from all databases on Web of Science and for all dates, the oldest publication dating 1995. This search term sequence provided a representative sample of the literature which included studies specific to the impacts of shipping on Arctic animals, rather than just the general effects of environmental change. The search terms elicited 47 papers, three of which were duplicates, resulting in 44 unique papers.

I further filtered the papers to review based on the papers' abstracts, and constructed a series of questions to ensure the papers were relevant to my research questions. Specifically, I retained a paper if it included an analysis or discussion of marine mammals, the Arctic, and commercial shipping. After reading the abstract of the 44 papers, I organized them by answering 'yes' or 'no' to each of the filtering questions and documented accordingly. If the paper did not answer 'yes' to all of the designated questions, it was discarded. The filtering questions eliminated 18 of these papers, which did not answer yes to each of the questions, and this led to retention of 26 papers retained for analysis. Although the 18 excluded papers were not used in the systematic analysis, they were used to inform the discussion section of this paper, specifically with regard to shipping management and regulations and climate change.

Next, I developed specific questions based on my research aims to extract data from papers included in the systematic review of the remaining publications that met the criteria for inclusion (*see Table 1*). The questions were constructed following a preliminary review of the literature (e.g., Hauser et al., 2018; Halliday et al., 2018, Laidre et al., 2015; Ghosh, S. & Rubly,

C., 2015), per the screening strategy of the ROSES systematic review protocol (Haddaway et al., 2017). This screening strategy eliminates papers obtained from the search terms that are only tangentially related to the topic, in this case shipping impacts on AMMs.

The screening questions were written to include papers that cover themes of legislation and policy measures designed to protect AMMs, direct and indirect effects of shipping on AMMs, and the general effects of climate change on marine mammals and Arctic habitats in the past several decades. I extracted data using the questions in Table 1 (*see Supplemental Information for full suite of detailed questions*). The data recorded were used to quantify the number of papers that answer or address each question in Table 1.

In particular, based on a preliminary review of the literature, I assessed whether each paper considered shipping impacts in terms of: noise pollution, ship strikes, oil spills, ballast water and/or other pollution, and/or other impacts (with an option to record other impacts); I also recorded if papers did not consider an impact of shipping. Next, I reviewed several biological effects of each type of shipping impact, including: habitat shifts, behavioral change, mortality, toxicological effects, other effects, or no biological effect considered for a given shipping impact. These impacts were chosen because they represent common consequences of shipping on marine mammals as seen in other literature (e.g., Hauser et al., 2018; Halliday et al., 2018, Laidre et al., 2015; Ghosh, S. & Rubly, C., 2015). Further, I assessed whether papers discussed, proposed, or evaluated regulations of shipping (*see details in Table 1 and Appendix 1*). Finally, I assessed whether each paper considered climate change, in terms of: warming, sea ice loss, variability or extreme events, changes in resources/prey (biotic), and/or other impacts (with an option to record other impacts).

If questions arose about whether a paper met the filtering criteria or responses to the questions in Table 1, multiple people (L. Dee and K. Peterson) reviewed the papers to ensure consistency, and the papers were discussed until we reached agreement, per the ROSES protocol.

*Table 1. Data extraction questions applied to papers included in systematic review. Questions were developed to gather data to address each thesis aim.*

| ***No.*** | ***Question*** |
|---|---|
| 1. | What impacts of shipping does this paper consider? |
| 2. | What are the biological impacts from the shipping impact of:<br>● Noise pollution<br>● Ship strikes<br>● Oil spills<br>● Ballast water pollution<br>● Other<br>● None considered |
| 3. | What are the biological impacts from the shipping impact of noise pollution/ship strikes/oil spills/ballast water pollution/other?<br>● Habitat shifts<br>● Behavioral change<br>● Mortality<br>● Toxicological effects<br>● Other<br>● NA: this paper did not consider this shipping impact |
| 4. | Does the paper consider or discuss shipping regulations?<br>● No<br>● Yes, discussed or mentioned<br>● Yes, as the focus of the paper |
| 5. | What regulations does the paper mention for the shipping impacts of ship strikes/oil spills/ballast water pollution/any impact not listed?<br>● Vessel route monitoring<br>● Ship speed reduction<br>● Employment of an AMM observer on ships<br>● Controlled transfer of invasive species (ballast water discharge)<br>● Gear recovery, fishing gear tagging and tracking, fisheries management/enforcement, reduction of plastic use on cruise ships |
| 6. | Does the paper propose future regulations?<br>● Yes<br>● No |
| 7. | Does evaluate the effect or potential effect of a regulation? |

| | |
|---|---|
| | ● Yes - If yes, elaborate on the effect and findings.<br>● No |
| 8. | What mammal species are considered in this paper?<br>● Bowhead whale (*Balaena mysticetus*)<br>● Beluga whale (*Delphinapterus leucas*)<br>● Narwhal (*Monodon monoceros*)<br>● Ringed seal (*Pusa hispida*)<br>● Bearded seal (*Erignathus barbatus*)<br>● Walrus (*Odobenus rosmarus*)<br>● Polar bear (*Ursus maritimus*)<br>● None<br>● Other |
| 9. | Does this paper consider climate change?<br>● No<br>● Yes, with data (empirical on trends and impacts)<br>● Yes, with model projections<br>● Yes, discusses qualitatively (no data or models)<br>● Other |
| 10. | What aspects of climate change?<br>● N/A<br>● Warming<br>● Sea ice loss<br>● Variability or extreme events<br>● Changes in resources/prey (biotic)<br>● other |
| 11. | Does the paper consider climate policy?<br>● Yes - If yes, elaborate<br>● No |
| 13. | What gaps does this paper identify? |

**Results**

The most commonly discussed Arctic marine mammal was bowhead whales, considered in 53.8% of analyzed papers, followed by the beluga whale (50% of papers) and by ringed seals, polar bears, and walruses in 42.3% of papers (Figure 1). The least discussed mammal species were blue whales, hooded seals, white-beaked dolphins, Dall's porpoise, brown bears, and Arctic foxes, each mentioned in only 3.8% of papers (Figure 1).

Noise pollution was by far the most commonly discussed shipping impact among the analyzed papers, as it was addressed in 65.4% of the papers (Figure 2). Of the papers that discussed noise pollution, the most significant biological impact was behavioral change, considered in 82.3% of papers, in which mammals altered foraging behaviors and attempted to avoid ships due to the harmful impacts of commercial ship noise (Figure 3). Acoustic masking, in which animals cannot effectively hear a signal of interest due to noise that overlaps with their hearing sensitivity, was discussed in 41.2% of papers (Figure 3).

The other shipping impacts that were discussed in at least a third of total papers were oil spills in 38.5% of papers and ship strikes in 34.5% of papers (Figure 2). Among papers that discussed oil spills, 90% discussed the toxicological impacts to mammals, however other biological impacts from oil spills were rarely discussed (Figure 5). Papers that discussed ship strikes primarily focused on direct mortality as the potential biological impact on AMMs; this was discussed in 88.9% of these papers (Figure 4).

Ballast water pollution was rarely discussed as a shipping impact on AMMs, as it was only mentioned in 11.5% of papers (Figure 2). All papers that discussed ballast water pollution mentioned toxicological effects on AMMs, such as hypothermia due to physical contact with oil or internal effects due to ingestion like secondary organ dysfunction, congested lungs, or damaged airways, as the main biological impact. Other types of biological and ecological impacts of shipping, such as bycatch, mother-pup separation, plastic waste pollution, and destruction of habitat, were only discussed in one or two papers. These papers comprised a small

portion of the total papers analyzed in this review, and thus were an insufficient sample size from which to draw patterns.

In this review, I found that 54% of papers mentioned regulations to mitigate these effects caused by various shipping activities, with an additional 11.5% discussing regulations as the main focus of the paper. Despite 65.5% of papers discussing shipping regulations in some form, only 58% proposed future regulations, and 46% evaluated the effect or potential effect of a regulation.

Both ship speed reduction and vessel route monitoring were the most frequently discussed regulatory mechanisms for both noise pollution and ship strikes (Figure 7 and Figure 8). Ship speed reduction was the most commonly proposed mitigation strategy for noise pollution, as 41.2% of papers that discussed noise pollution recommended or assessed this measure (Figure 7). Vessel route monitoring closely followed with 35.3% of noise pollution papers recommending this method (Figure 7). Among papers that considered ship strikes, 66.7% discussed ship speed reduction, while 55.6% considered vessel route monitoring (Figure 8). Among papers that discussed oil spills, 30% discussed vessel route monitoring as a regulatory mechanism, followed by 20% of papers that discussed ship risk assessment, where hazards are assessed and rectified on individual ships (Figure 9). In papers that discussed noise pollution or oil spills, the number of papers that did not discuss any regulatory mechanisms outweighed those that did, especially for oil spills. 52.9% of papers discussing noise pollution did not analyze any current regulations or propose any new ones to mitigate the harmful impact of noise pollution (Figure 7). Further, 60% of papers discussing oil spills did not discuss or propose any

regulations, which was double the leading suggested regulation of vessel route monitoring for this group of papers (Figure 9).

Climate change was more thoroughly discussed in some papers and entirely disregarded in others. 84.6% of the papers analyzed addressed climate change qualitatively, with no data or models, while only 3.8% of papers used model projections to depict climate change and 3.8% included data on climate trends and impacts. 7.7% of the papers did not address climate change at all. The vast majority of papers, 81%, did not consider any policies related to climate change despite frequent discussion of multiple climate change impacts. All papers that discussed climate change also discussed sea ice loss (Figure 11). General warming in the Arctic region was also frequently discussed, as it was mentioned in 66.7% of papers (Figure 11). Changes in resources and prey for marine mammals was considered in 45.8% of papers, and variability and extreme events were mentioned in 37.5% of papers (Figure 11).

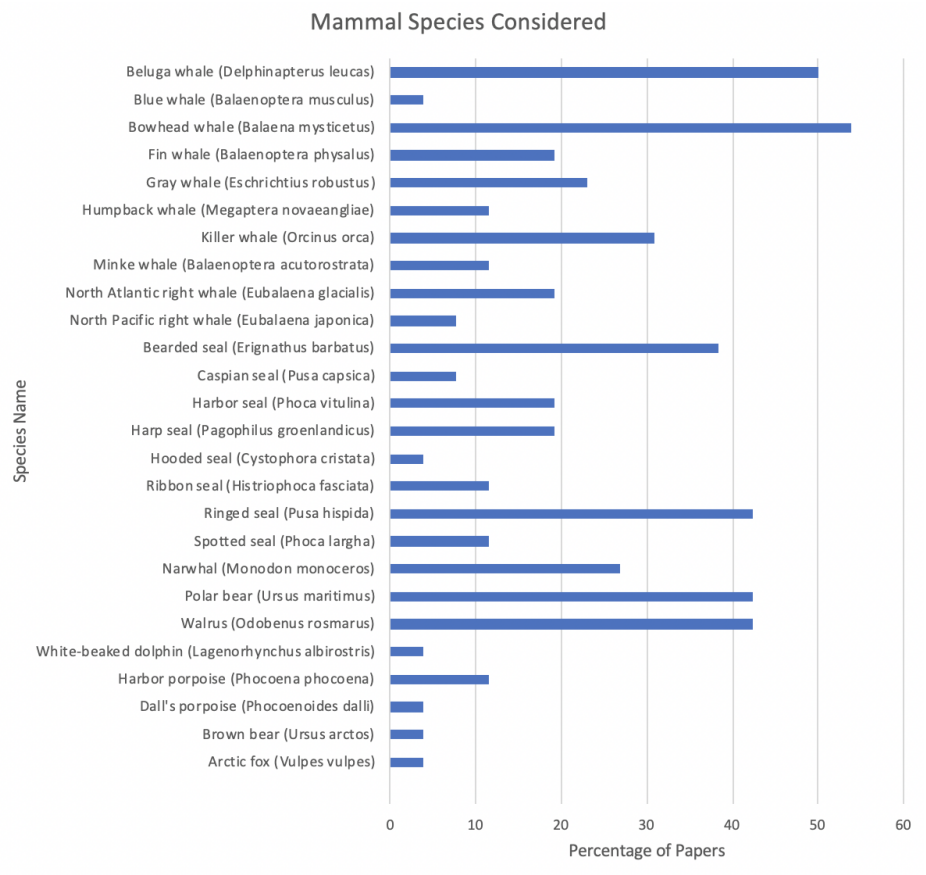


*Figure 1. Percentage of total papers analyzed which referenced or discussed various Arctic mammal species. The most commonly discussed mammals included bowhead and killer whales, ringed and bearded seals, polar bears, walruses.*

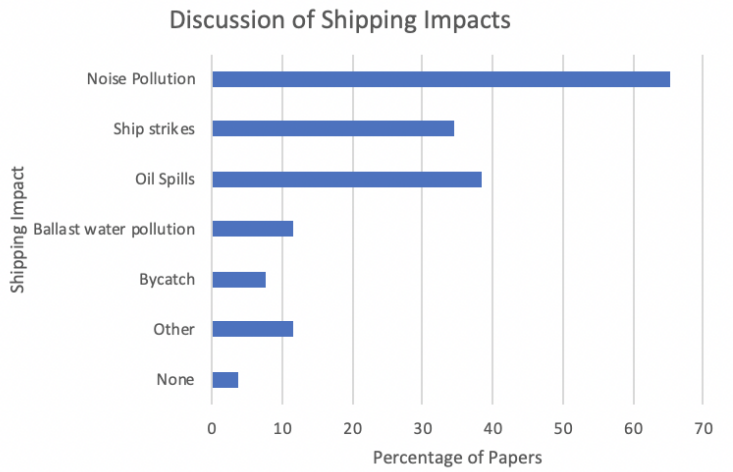

*Figure 2. Percentage of total papers analyzed which discuss common impacts of commercial shipping in the Arctic. Noise pollution was the most frequently discussed shipping impact, followed by oil spills and ship strikes.*

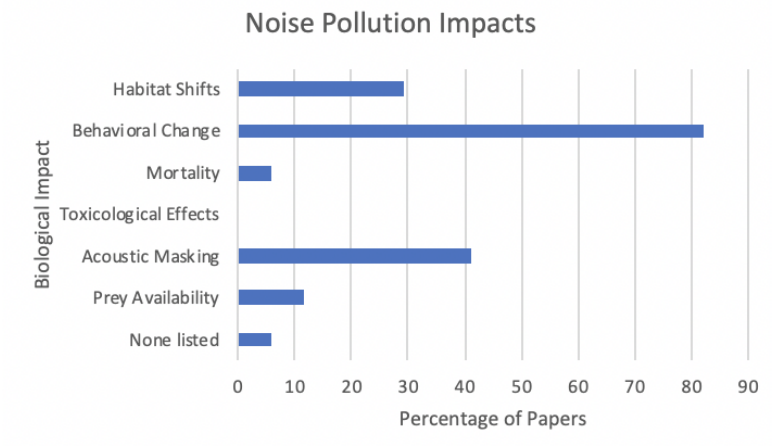


*Figure 3. Percentage of papers analyzed that discussed common biological impacts of noise pollution out of total papers that considered noise pollution. Behavioral changes, such as risk avoidance and foraging cessation, were very commonly discussed, followed by acoustic masking and habitat shifts.*

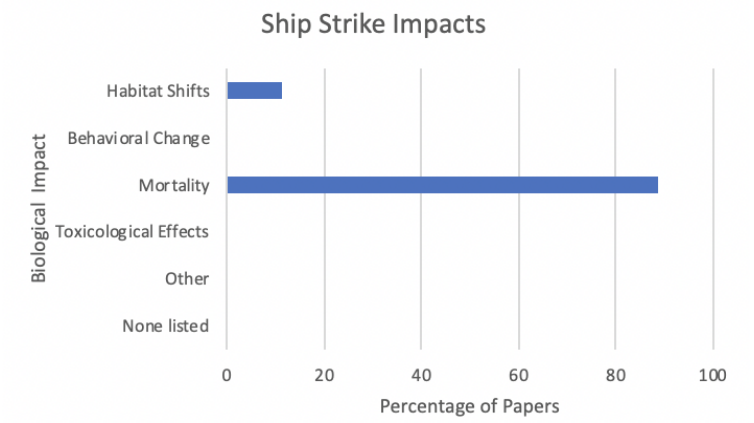


*Figure 4. Percentage of papers analyzed that discussed common biological impacts of ship strikes out of total papers that considered ship strikes. Mortality was the only commonly*

*discussed biological impact as a result of ship strikes. Habitat shifts were the only other impact discussed, albeit infrequently.*

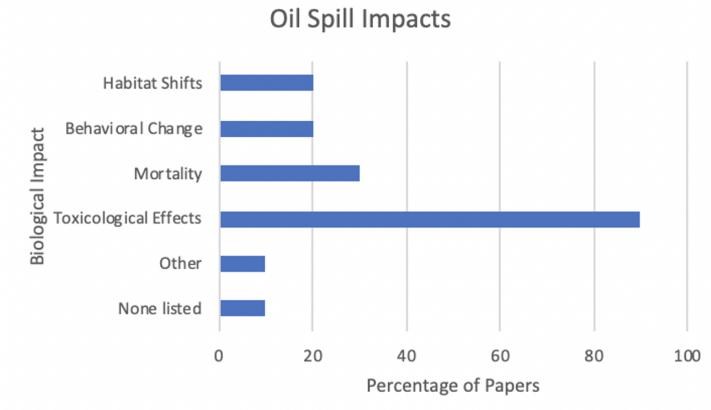


*Figure 5. Percentage of papers analyzed that discussed common biological impacts of oil spills out of total papers that considered oil spills. Toxicological effects were the main impact of oil spills considered in the papers, followed by mortality. Habitat shifts and behavioral change were both equally infrequently discussed.*

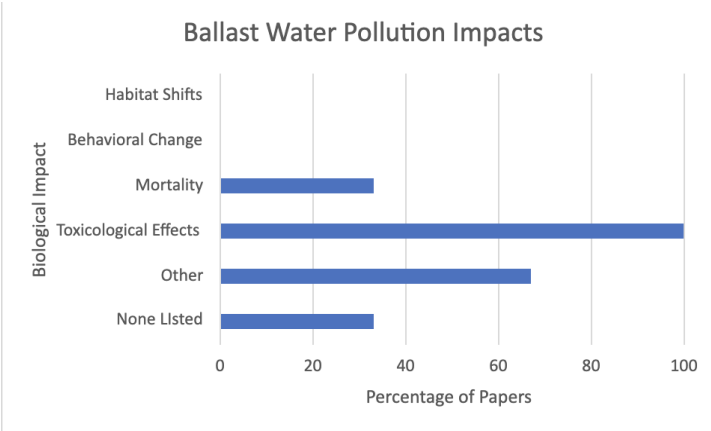


*Figure 6. Percentage of papers analyzed that discussed common biological impacts of ballast water pollution out of total papers that considered ballast water pollution. Toxicological effects were discussed in all papers that considered ballast water pollution. Loss of biodiversity and prey availability were other impacts that several papers considered.*

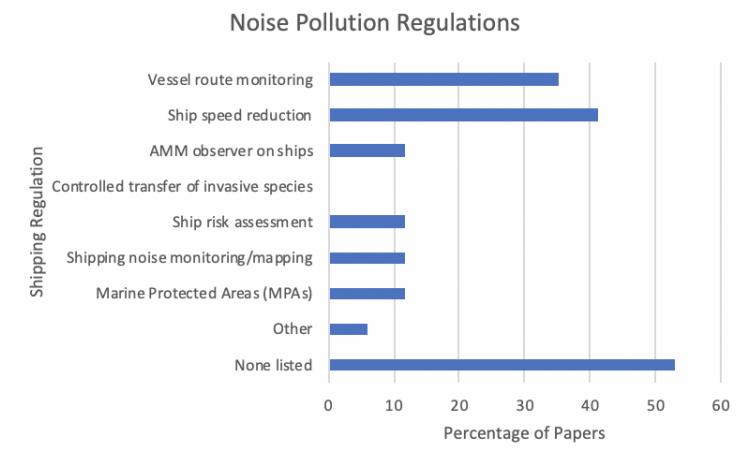


*Figure 7. Percentage of papers analyzed that discussed common shipping regulations for noise pollution out of papers that considered noise pollution. Ship speed reduction and vessel route monitoring were both frequently discussed regulatory mechanisms for noise pollution.*

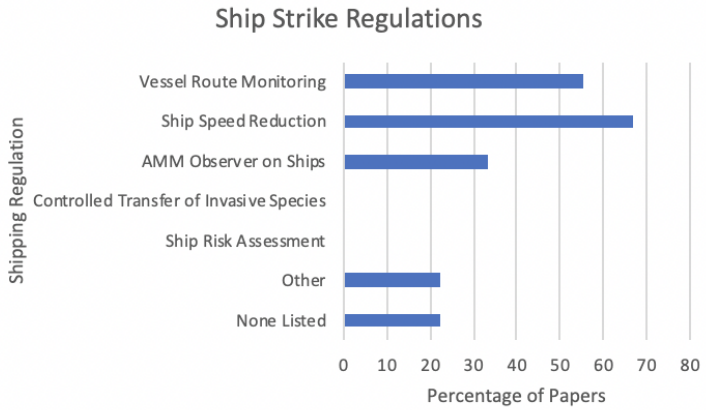


*Figure 8. Percentage of papers analyzed that discussed common shipping regulations for ship strikes out of total papers that considered ship strikes. Ship speed reduction and vessel route monitoring were both frequently discussed regulatory mechanisms for ship strikes. Employing an AMM observer on ships was also commonly considered.*

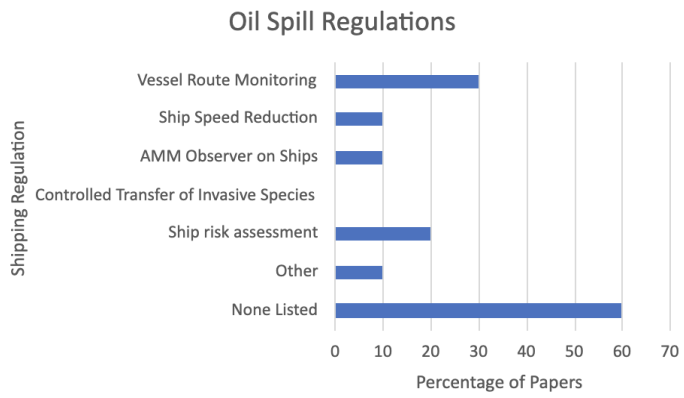


*Figure 9. Percentage of papers analyzed that discussed common shipping regulations for oil spills out of total papers that considered oil spills. Vessel route monitoring and ship risk assessment were the only two commonly discussed regulations for oil spills.*

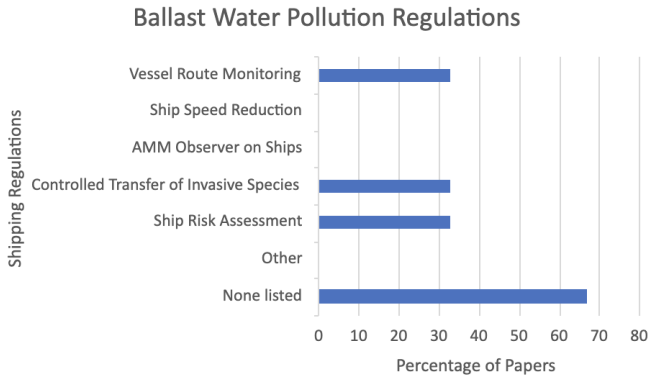


*Figure 10. Percentage of papers analyzed that discussed common shipping regulations for ballast water pollution out of total papers that considered ballast water pollution. Vessel route monitoring, controlled transfer of invasive species, and ship risk assessment were all equally discussed regulations for ballast water pollution.*

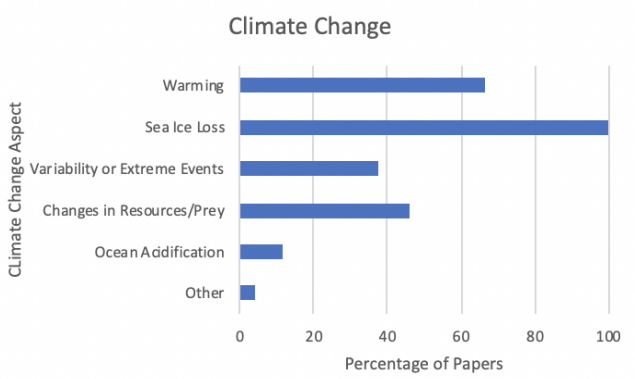


*Figure 11. Percentage of papers analyzed that considered various aspects of climate change out of total papers that discussed climate change either qualitatively with no models, used model projections to depict climate change, or included data on climate trends and impacts. Sea ice loss was considered in every paper, and warming of the Arctic climate was also fairly frequently discussed.*

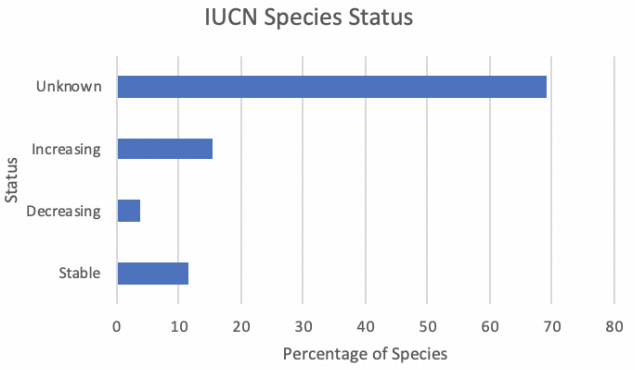


*Figure 12. Percentage of each mammal species considered whose population is designated as unknown, increasing, decreasing, or stable by the International Union for Conservation of Nature Red List of Threatened Species. The majority of species' population trends were considered unknown.*

## Discussion

This literature review aimed to systematically assess current knowledge of the consequences of increased commercial shipping using trans-Arctic routes for marine mammals in the face of sea ice melt and a warming climate. I examined the most prominent effects of shipping on arctic marine mammals and the current and proposed tools for mitigating these negative impacts. Bowhead whales, ringed and bearded seals, polar bears, and walruses were the most frequently considered marine mammals in these papers. Of the shipping impacts that affected these mammals, noise pollution was by far the most common, with oil spills and ship strikes also being highly represented in the literature (both over 30% of papers). The most notable biological effects of these shipping impacts were behavioral change due to noise disturbance, specifically alterations in activities such as feeding and breeding practices, injury and mortality from strikes, and toxicological effects from oil spills. Popular policy or regulatory mechanisms that were discussed for each of these impacts included ship speed reduction to emit less noise and reduce likelihood of strikes, and vessel route monitoring and alteration of routes away from AMM habitats to limit sound disturbance and likelihood of collisions. According to 30% of papers that consider oil spills (Figure 9), changing routes to reduce proximity of ships to AMMs would also reduce the chance of oil polluting their habitats.

Many papers stated that acoustic masking, which is the inability of an animal to perceive sounds needed for hunting and communication due to significant surrounding noise, was a common impact on AMMs from vessel noise (Figure 3). Noise pollution was the most frequently discussed impact of shipping activity, discussed in about 65% of papers (Figure 2), yet there is a need for data on acoustic behavioral thresholds and data on how individual animals actually react

to noise. Aulanier et al. (2017) and Baumgartner et al. (2014) accomplish this by assessing the contribution of ship noise to Arctic soundscapes and establishing the impacts of hearing threshold shifts on mammals. However, few studies from my systematic review have established hearing thresholds, especially when it comes to characterizing open water background noise, and actually applied acoustic monitoring methods to shipping noise impact mitigation. Data like this, in conjunction with continued vessel monitoring data and establishment of baselines for noise levels in the Arctic, is necessary for determining what noise levels are safe for AMMs and would better inform policy decisions by generating achievable goals for noise reduction from current levels (Insley et al., 2017; Farcas et al., 2020). Oil spills were also frequently considered in the papers in my systematic review, and seem to be more thoroughly assessed in policy discussions than other shipping impacts (Cameron et al., 2010; Boveng et al., 2013; Meier et al., 2014; Silber & Adams, 2019). There are currently significant regulations in place to limit the impact of oil on AMMs and the environment as a whole, as oil pollution has long been an area of focus in the Arctic, and public awareness has continued to increase in recent years (Leschine, 2002). This could be in part due to greater visibility of oil spills, both physically and in the media, in comparison to less obvious shipping impacts like noise and ballast water pollution (Leschine, 2002). However, as interest in oil and gas exploration continues to increase, data on species distribution in comparison to the distribution of oil sources in the region needs to be acquired so that AMMs' potential exposure to oil is known (Nevalainen et al., 2019). Many papers do not detail the actual effects of oil on animal behavior, especially for specific species within the Arctic, instead limiting this discussion to the mere mention of illness and/or eventual death. Smultea et al. (2016) provides this type of observational data regarding polar bear behavior in response to oil drilling operations that needs to be acquired for more individual species; however,

observations of mammal response to actual spills is still lacking. Observations on how oil impacts aspects of species behavior such as grooming, feeding, and migration or distribution will be increasingly necessary as oil and gas development continues in the Arctic (Baumgartner et al., 2014; Smultea et al., 2016).

From this analysis, I found that the main knowledge gap is the lack of specific biological and ecological information on species. Typically, most papers in my analysis only included a short list of species that may be impacted by shipping, without elaborating on the biological mechanisms or repercussions. Indeed, as shown in Figure 1, only a few species are discussed in any scope in at least 30% of papers. One potential reason for this gap is that species distribution and population monitoring data is scarce, especially over multiple seasons (Boveng et al., 2013). The lack of both biological and ecological data make it incredibly difficult to quantify behavioral or habitat changes from shipping impacts and subsequently determine the least harmful shipping routes (Pirotta et al., 2017). For example, Pirotta et al. (2017) highlights the need for additional data on beluga distributions over multiple seasons in order to gain insight into the variability of their habitat through space and time, which can be used to assess how vulnerable this species is to shipping impacts. With this information on species distributions and habitat needs, policy solutions to reduce shipping impacts could be identified. For example, Yurkowski et al. (2018) identifies ringed seal hotspots and pupping grounds and overlap between proposed icebreaking activity and areas of high seal density; thus, with critical habitat information, they were able to evaluate "safe" distances and speeds at which ships should travel to minimize disturbance to these animals. In comparison to other Arctic mammals, the species that are considered endemic to the Arctic, such as beluga and bowhead whales, narwhals, ringed and bearded seals, walruses, and polar bears, are discussed in considerable quantity (>35% of papers) and researchers have

acquired more population data on them (Figure 1). However, species that are not considered endemic are largely neglected in literature, as they are mentioned in less than 10% of papers in my study (Figure 1). According to the IUCN Red List, the population status of most of these species is unknown (Figure 12), except for the North Pacific right whale, whose population is decreasing; the blue whale, fin whale, humpback whale, and harp seal, whose populations are increasing; and the gray whale, brown bear, and arctic fox, whose populations are considered stable (IUCN, 2021). Improved data on the spatial distributions of AMMs, as well as more data on vessel traffic, would aid both researchers and policymakers in better determining overlap between AMM habitat and ship routes (Halliday et al., 2017). This would allow for policymakers to adjust shipping routes to minimize impact on species.

The second most prominent knowledge gap that I found is long-term data on the effects of vessel disturbance on AMMs. There is not sufficient existing information on the long-term repercussions to AMMs when species are impacted by shipping due to the fact that there are few long-term monitoring efforts in place. Because the rapid increase in Arctic shipping from sea ice melt is a relatively recent trend, there is a dearth of long-term data in terms of consequences of vessel disturbance on AMMs. The oldest paper in the Web of Science results for my search terms was published in 1995, which underscores how impacts on AMMs are a relatively new concern for conservationists and is a developing area of research. As this is a burgeoning area of research, it follows that there are limited studies with long term data on how vessels affect AMMs. The longest study in my review in which temporal data was gathered following a shipping impact on AMMs was eight years (Wilson et al., 2017). This study assessed the impact of icebreaking vessels on the breeding habitat of Caspian seals (Wilson et al., 2017). Most studies that followed

the effect of shipping activity on AMM species over time were limited to just a few years. Halliday et al. (2019) assessed decreasing beluga vocalizations due to vessel traffic over several years. Bearded seals, ringed seals, bowhead whales, and beluga whales' auditory masking tendencies were assessed before and after vessel slowdown (Pine et al., 2018). Polar bear behavior was examined near icebreaker operations at exploratory drilling sites in the Chukchi Sea, but only for one season (Smultea et al., 2016). Two government reports detail past studies in which the effects of shipping impacts like bycatch or oil and gas activity were assessed over time for bearded seals and ribbon seals (Cameron et al., 2010; Boveng et al., 2013). I found that no temporal assessment whatsoever of shipping impacts exists for species that are not commonly considered endemic. There is a need for more attention on the impacts on behavior for particular species; see Cameron et al. (2010), Boveng et al. (2013), and Yurkowski et al. (2018), which examine shipping impacts thoroughly on one mammal species. These papers provide a much more detailed analysis of the biological effects of shipping on a certain species, rather than a vague assessment that ecompasses all marine mammals, and are therefore able to offer more suggestions for specific regulatory measures based on the effect of shipping on species behavior. For example, Halliday et al. (2017) examines how beluga whale behavior has changed, specifically their vocalizations, in response to vessel traffic; this in-depth analysis of a specific species allowed for suggestion of policy measures specific to begulas based on both their spatial and temporal distribution. Data like this is important as it allows policymakers to assess the severity and longevity of an impact, such as noise pollution, on different species. Long term data on how AMM responds to vessels is therefore crucial for identifying mitigation techniques and developing regulations that prevent the worst impacts of shipping on AMMs. Many researchers stated that despite their findings, these gaps in data need to be addressed in order to validate their

policy or regulation suggestions (Hovelsrud et al., 2008, Jing et al., 2012, Yurkowski et al., 2018; Farcas et al., 2020).

In addition to spatial and temporal ecological data, many papers in my review highlighted the need for other types of data to inform policy in the Arctic to minimize impacts on AMMs. Continued monitoring of sea ice extent as well as increased monitoring efforts of vessel route use and AMM movement and distribution among different regions, species, and subpopulations is a potentially effective technique for awareness and subsequent threat mitigation (Silber & Adams, 2019). Farcas et al. (2020) also highlights the importance of using acoustic modelling in conjunction with shipping density data as the best approach in terms of policymaking for noise pollution, because shipping density data alone is not adequate.

In my review, I found that papers that analyzed policy strategies in detail were lacking. While many papers made general suggestions for future regulations, most did not thoroughly examine the effects of any current or proposed regulations. Papers that did inspect policy in detail included the two government publications reviewing bearded and ribbon seals, which assessed various legislative measures that have been enacted in Arctic Circle countries over the past several decades, along with any global measures (Cameron et al., 2010; Boveng et al., 2013). Edwards & Evans (2017) offered a more contemporary view of current policy in light of marine spatial planning practices, detailing current legislation that impacts this practice as well as recommendations for future governance and management. Other papers focused more on mammal vulnerability to shipping rather than management practices, and therefore did not give in-depth policy analyses or suggestions (Clarke et al., 2013; Baumgartner et al., 2014; Farcas et al., 2020). Further, they did not assess the implications of such proposals, instead offering

general policy suggestions, such as vessel slowdown, that are more widely and generally applicable. The majority of papers in this review addressed current shipping legislation or made suggestions for future policy, but many did not evaluate the effect or potential effect of these regulations.

While there is a need for more in depth policy analysis in regards to shipping impacts on AMMs, there were some papers from this literature review that discussed policies that have been enacted so far. Throughout the Arctic Circle, regulations concerning oil pollution and ballast water discharge are clearly defined, have been developed and adjusted over many years, and often are required rather than merely suggested (Cameron et al., 2010; Boveng et al., 2013). Multiple countries have created regulations for management and preparedness for oil spills. The Oil Pollution Act of 1990 attempts to reduce the hazardous effects of oil spills by addressing spill prevention, preparedness, and response in the United States, along with organizations like the National Oceanic and Atmospheric Association, Environmental Protection Agency, and US Coast Guard (Jing et al., 2012; Boveng et al., 2013). Alaska specifically has preparedness requirements and contingency plans for oil spills, as well as general waste management and air quality requirements (Boveng et al., 2013). The Canada Shipping Act allows the Governor in Council to make regulations for protecting the marine environment and prevention and reduction of release by vessels of aquatic organisms or pathogens that may be deemed hazardous (Jing et al., 2012). The Maritime and Coastguard Agency and Norwegian Maritime Directorate have been working to regulate ballast water management in Norway (Jing et al., 2012). The Russian Federation prohibits the discharge of oily ballast water from vessels traversing the Northern Sea Route (Jing et al., 2012). Globally, the International Maritime Organization for Control and

Management of Ship's Ballast Water and Sediments required all ships to establish a ballast water management system between 2009 and 2016 (Jing et al., 2012). Overall, the most effective management system was determined to consist of ballast water treatment and a series of management practices like establishment of ballast water exchange areas, ship operational procedures, alteration of routes, evaluation of currently available technologies, and human health and environmental risk assessment (Jing et al., 2012).

Several papers within my literature review thoroughly evaluated the effects of their suggested regulatory mechanisms. For example, McWhinnie et al. (2018) offered detailed insight into previous measures that have been successful in reducing the occurrence of noise pollution and ship strikes and offers further solutions. According to McWhinnie et al. (2018), mandatory exclusion zones, areas where ships are not allowed to travel, are the only proven management tool that protects AMMs from vessels by removing all risk. Other preventative measures could include vessel slowdown and buffer zones surrounding marine protected areas to minimize noise pollution and ship strikes (McWhinnie et al., 2018). Thoroughly evaluated policy such as this is essential to the creation of future shipping management plans.

As climate change continues to exacerbate Arctic sea ice melt, it is particularly important to develop shipping management strategies that take climate change and its consequences into account given the link between warming climates, further sea ice melt, and increases in shipping activity. Despite this need, I found that climate policy was severely underrepresented. Very few papers -- only 19% -- analyzed in this literature synthesis discussed climate policy or regulations, despite recognizing that melting sea ice has been one of the greatest threats to AMMs over the past several decades and has allowed for the rise in commercial shipping (Wang & Overland, 2015; Silber & Adams, 2019). Only 3.8% of papers used model projections to depict climate

change (Wang & Overland, 2015), and 3.8% included data on climate trends and impacts (Boveng et al., 2013), which indicates that any suggestions on policy that these papers are making are generally not also taking into account predicted climate trends. However, considerations of climate change on sea ice and shipping will be increasingly necessary for the establishment of adequate regulatory mechanisms and overall protection of AMMs as climate change is predicted to worsen sea ice melt (Mumby et al., 2017; Wang & Overland, 2015). In addition to the indirect threats of climate change through increased shipping, there are several direct effects of melting sea ice on AMMs, which was out of the scope of this review focused on shipping. Indeed, some AMM species rely on sea ice for reproduction, molting, resting, and feeding, while others use it but do not completely depend on it (Laidre et al., 2015). There are a number of direct health effects associated with environmental changes, like loss of habitat, temperature stress, and exposure to severe weather (Burek et al., 2008). Despite the direct and indirect effects of sea ice melt on AMMs, there are no regulations currently in place, either nationally or internationally, that effectively address sea ice melt (Boveng et al., 2013). Additionally, in the few papers I analyzed that do mention some sort of climate policy, none of the five addressed any current or proposed regulation that involved sea ice and policies that mitigate the effects of its loss. The most adequately addressed facet of climate change in Arctic policy in the papers reviewed in this synthesis seems to be emissions (Cameron et al., 2010; Boveng et al., 2013; Eriksen et al., 2020). The UN Framework Convention on Climate Change and the Paris Agreement addresses greenhouse gas emissions and global warming (UNFCCC). In addition, the Convention on Long-Range Transboundary Air Pollution, created in 1983, made internationally legally binding regulations for the reduction and control of major air pollutants

(Cameron et al., 2010). Many aspects of climate change were rarely considered in the literature I reviewed, making the suggested regulatory mechanisms for shipping potentially less effective.

**Conclusions**

This literature review analyzes a representative sample of current literature in order to address the aspects of commercial Arctic shipping that impact various species of Arctic marine mammals, as well as what type of regulatory mechanisms are commonly proposed in response to these impacts, in order to inform future research directions and identify gaps in current knowledge. I found that noise pollution is the most frequently discussed shipping impact in current literature, followed by vessel strikes and oil pollution (Figure 2). Common biological effects of these shipping occurrences are acoustic masking, behavioral change, and mortality. Of papers that discussed these impacts, some suggested regulations included vessel route monitoring, ship speed reduction, and ship risk assessment. Although most papers discussed current shipping regulations or proposed future ones, most did not evaluate the effect of these regulations on AMMs, as very few AMM species are discussed in any considerable quantity. More species-specific data on habitat use and distributional patterns and behavioral observations are needed to validate policy suggestions. Most papers considered broad climate change aspects, such as warming and melting sea ice, but the vast majority did not discuss any sort of climate policy. This will be even more crucial to AMMs' ability to utilize their habitat and overall survival as climate change continues to worsen, so it is important to take into consideration predicted climate trends in legislation and policy.

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**Supplemental Information**

**Appendix 1: The questionnaire used for data extraction from the papers.**

Data Extraction/Review

Questions Responses 26

# Data Extraction/Review

Form description

Author Last Name and Year *

Short answer text

Paper Title *

Short answer text

Journal Name *

Short answer text

What impacts of shipping does this paper consider? *

- [ ] None
- [ ] Noise Pollution
- [ ] Ship strikes / Mortality or injury

- [ ] Ballast water pollution
- [ ] Other…

What are the biological impacts from the shipping impact of noise pollution?

- [ ] Habitat shifts
- [ ] Behavioral change
- [ ] Mortality
- [ ] Toxicological effects
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other…

What are the biological impacts from the shipping impact of ship strikes?

- [ ] Habitat shifts
- [ ] Behavioral change
- [ ] Mortality
- [ ] Toxicological effects
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other…

What are the biological impacts from the shipping impact of oil spills?

Habitat shifts

- [ ] Behavioral change
- [ ] Mortality
- [ ] Toxicological effects
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other…

What are the biological impacts from the shipping impact of ballast water pollution?

- [ ] Habitat shifts
- [ ] Behavioral change
- [ ] Mortality
- [ ] Toxicological effects
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other…

What are the biological impacts of any shipping impact not listed?

- [ ] Habitat shifts
- [ ] Behavioral change
- [ ] Mortality
- [ ] Toxicological effects

- [ ] Other...

Does the paper consider or discuss shipping regulations?

- ( ) No
- ( ) Yes, discussed or mentioned
- ( ) Yes, as the focus of the paper

What regulations does the paper mention for the shipping impact of noise pollution?

- [ ] Vessel route monitoring
- [ ] Ship speed reduction
- [ ] Employment of an AMM observer on ships
- [ ] Controlled transfer of invasive species (ballast water discharge)
- [ ] Ship risk assessment
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other...

What regulations does the paper mention for the shipping impact of ship strikes?

- [ ] Vessel route monitoring
- [ ] Ship speed reduction
- [ ] Employment of an AMM observer on ships

- [ ] Ship risk assessment
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other...

What regulations does the paper mention for the shipping impact of oil spills?

- [ ] Vessel route monitoring
- [ ] Ship speed reduction
- [ ] Employment of an AMM observer on ships
- [ ] Controlled transfer of invasive species (ballast water discharge)
- [ ] Ship risk assessment
- [ ] NA: this paper did not consider this shipping impact
- [ ] Other...

What regulations does the paper mention for the shipping impact of ballast water pollution?

- [ ] Vessel route monitoring
- [ ] Ship speed reduction
- [ ] Employment of an AMM observer on ships
- [ ] Controlled transfer of invasive species (ballast water discharge)
- [ ] Ship risk assessment
- [ ] NA: this paper did not consider this shipping impact

What regulations does the paper mention for any shipping impact not listed?

- [ ] Vessel route monitoring
- [ ] Ship speed reduction
- [ ] Employment of an AMM observer on ships
- [ ] Controlled transfer of invasive species (ballast water discharge)
- [ ] Ship risk assessment
- [ ] NA: this paper did not consider a shipping impact not originally listened
- [ ] Other…

Does the paper propose future regulations?

- ( ) Yes
- ( ) No

Does the paper evaluate the effect or potential effect of a regulation?

- ( ) Yes
- ( ) No

If yes, elaborate on the effect and findings:

Long answer text

What mammal species are considered in this paper?

- [ ] Bowhead whale (Balaena mysticetus)
- [ ] Beluga whale (Delphinapterus leucas)
- [ ] Narwhal (Monodon monoceros)
- [ ] Ringed seal (Pusa hispida)
- [ ] Bearded seal (Erignathus barbatus)
- [ ] Walrus (Odobenus rosmarus)
- [ ] Polar bear (Ursus maritimus)
- [ ] None
- [ ] Other...

Does this paper consider climate change?

- ( ) No
- ( ) Yes, with data (empirical on trends and impacts)
- ( ) Yes, with model projections
- ( ) Yes, discusses qualitatively (no data or models)
- ( ) Other...

What aspects of climate change?

- [ ] warming
- [ ] sea ice loss
- [ ] variability or extreme events
- [ ] changes in resources/prey (biotic)
- [ ] Other...

Does this paper consider climate policy?

- ( ) Yes
- ( ) No

If yes, elaborate:

Long answer text

What gaps does this paper identify?

Long answer text