Increased Shipping Activity and Marine Mammals in Baffin Bay and Davis Strait: Developing a Low-Impact Shipping Corridor.

by

OWEN RHYS HUGHES

A Thesis Submitted to the Faculty of Social and Applied Sciences

in Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE IN ENVIRONMENT AND MANAGEMENT

Royal Roads University

Victoria, British Columbia, Canada

Supervisor: Dr. WILLIAM D. HALLIDAY

FEBRUARY, 2025

COMMITTEE APPROVAL

The members of Owen Rhys Hughes' Thesis Committee certify that they have read the thesis titled "Increased Shipping Activity and Marine Mammals in Baffin Bay and Davis Strait: Developing a Low-Impact Shipping Corridor." and recommend that it be accepted as fulfilling the thesis requirements for the Degree of Master of Science in Environment and Management:

[Dr. Robert Newell] [signature on file]

Final approval and acceptance of this thesis is contingent upon submission of the final copy of the thesis to Royal Roads University. The thesis supervisor confirms to have read this thesis and recommends that it be accepted as fulfilling the thesis requirements:

[Dr. William D. Halliday] [signature on file]

Abstract

As the Canadian Arctic warms at a rate far surpassing the global average, the changing sea ice regime invites increased development and shipping activity. This increased activity introduces greater anthropogenic pressures on cetaceans, resulting in increased risk of strikes, behavioural disturbances, and other negative impacts. The Canadian waters of Baffin Bay and Davis Strait are experiencing this increased vessel traffic as part of the Northwest Passage. Managing these worsening impacts is of the utmost importance to preserve the sensitive ecosystem of the Canadian Arctic. This thesis explores how increasing vessel traffic trends are overlapping with cetacean distributions and assesses the placement of a low-impact shipping corridor aiming to reduce this overlap. The low-impact corridor is compared to an existing shipping corridor that did not account for ecological inputs. The outcomes of this work and the identified low-impact corridor can be used to inform sustainable development in the Canadian Arctic.

Acknowledgements

This thesis represents the culmination of not only my passion and interest in marine mammal conservation, but also of the support of those around me. I'd like to thank the people that have I have been able to lean on throughout these past few years while working on my thesis project. First, I would like to give thanks to the owners of the data that I had the privilege of working with. Whale tagging data provided by multiple researchers at Fisheries and Oceans Canada and the Greenland Institute of Natural Resources. Satellite AIS data were provided by the Marine Environmental Observation, Prediction, and Response Network through an agreement with exactEarth. Thank you to my supervisor, Bill, for answering my out-of-the-blue email back in 2022 and offering me the opportunity to join the world of Arctic conservation research. Bill's patience and support during this process has been a huge motivation to produce the highest quality work I can and to contribute valuable work to our field of study. Thank you to Rob Newell, my sole committee member, who offered insight and feedback that I would not have considered without him. Finally, I would like to thank and acknowledge my wife and family. My wife Emma has supported, challenged, and motivated me more than she could ever realize, and I truly believe I could not have accomplished what I have without her. To my mom Josie, my dad Brian, my brother Alex, and my sister Carlie, thank you for your unconditional support and especially for letting me ramble to you on the phone every so often.

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1. Introduction

The Canadian Arctic is experiencing the warming effects of climate change at triple the rate of the global average (Bush & Lemmen, 2019). Such effects include a reduction of sea ice extent and volume (Pongolini et al., 2017; Bush & Lemmen, 2019). Summer sea ice area has been declining at a rate of 5-20% per decade in the Canadian Arctic, with projections indicating that sea ice-free summers could become a reality by mid-century in the 2000s (Bush & Lemmen, 2019). Recent studies have connected the reduction in sea ice with an increasing volume of shipping activity in the Canadian Arctic, with shipping traffic through the Northwest Passage (NWP) having more than doubled in distance travelled from 2013-2019 (Dawson et al., 2018; PAME, 2019; Pizzolato et al., 2016). The NWP is a shipping route through the Canadian Arctic that reduces travel distance between western Europe and eastern Asia by roughly 9000km when compared to traveling through the Panama Canal (Khon et al., 2010). The NWP also serves as a primary route for resupply for several remote Arctic communities and industries, acts as a popular destination for marine tourism, and encompasses several areas of ecological, economic, and cultural significance (Dawson et al., 2018, 2020). As shipping activity continues to grow and anthropogenic impacts on ecosystems and wildlife in the NWP increase, so does the need for implementing management solutions to minimize the negative impacts of vessel traffic.

Exposure to vessel traffic negatively impacts marine mammal populations. Threats such as ship strikes (Vanderlaan & Taggart, 2009), contamination and pollution (Williams et al., 2015), and underwater noise (Simmonds et al., 2014) are all risk factors for populations of whales exposed to vessel traffic. Underwater noise pollution causes a serious impact on marine mammals through acoustic masking, feeding interruption, habitat avoidance, as well as other behavioural disturbances (Gomez et al., 2016). Due to lower historical levels of anthropogenic activity, marine mammals native to the Canadian Arctic may have a higher sensitivity to adverse impacts from vessel traffic when compared to marine mammals from more developed regions (Halliday et al., 2020). The exposure of marine mammals to vessel traffic, and the resulting behavioural changes, can also negatively impact the Inuit communities that rely on these species as a food source (Ford, 2009; Halliday et al., 2022).

Current mitigation measures to reduce the impacts of vessel traffic on marine mammals include the development of exclusion zones, restrictions on vessel speeds, and the implementation of shipping corridors (McWhinnie et al., 2018). While efforts toward exclusion from areas for cetacean conservation has been shown to be an effective management strategy (Vanderlaan & Taggart, 2009), existing areas that focus on cetacean conservation in Canada, such as marine protected areas, do not always intersect with areas of high marine mammal concentrations (Halliday et al., 2018) and therefore may not be effective candidates for exclusion areas. This problem was demonstrated when Halliday et al. (2018) found that only a small proportion of two marine protected areas in the Canadian Arctic (the Tarium Niryutait Marine Protected Area and the Anguniaqvia Niqiqyuam Marine Protected Area) overlap with high whale concentrations.

Vessel speed has been shown to have a direct connection with the probability of lethal ship strikes with respect to whales (Vanderlaan & Taggart, 2007) and for reducing the underwater noise created by ships (MacGillivray and de Jong, 2021). The Port of Vancouver conducted a voluntary vessel slowdown study in 2018 in Haro Strait (Canada) and found the slowdown resulted in a 15.3% reduction in time that foraging killer whales (*Orcinus orca*) were affected by vessel traffic (Vancouver Fraser Port Authority, 2019).

The implementation of shipping corridors has also been demonstrated to be an effective conservation measure by diverting vessel traffic away from marine mammal populations. Designing a shipping corridor that avoids areas of high marine mammal densities can reduce the impacts of vessel traffic on local marine mammals, while providing a clear route for shipping traffic to follow. The adjustment of a shipping corridor in the Bay of Fundy away from a Right Whale Conservation Area resulted in a 62% reduction in lethal ship-strikes on Northern Atlantic right whales (*Eubalaena glacialis*) (Vanderlaan et al., 2008).

This study examines the Canadian waters of Baffin Bay and Davis Strait, a portion of the Northwest Passage between Baffin Island (Canada) and Greenland (Denmark). This region is considered a hotspot for abundance and species diversity in the Canadian Arctic, providing valuable habitat for several species of both endemic and migratory marine mammals (Yurkowski et al, 2019). The species native to this area, a subset of which are examined in this study, are: bowhead whales (*Balaena mysticetus*), beluga (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), northern bottlenose whales (*Hyperoodon ampullatus*), minke whales (*Balaenoptera acutorostrata*), harbour porpoise (*Phocoena phocoena*), ringed seals (*Pusa hispida*), bearded seals (*Erignathus barbatus*), harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), harbour seals (*Phoca vitulina*), and Atlantic walrus (*Odobenus rosmarus rosmarus*).

There are many Inuit communities spread along the Canadian and Greenlandic coasts lining Davis Strait and Baffin Bay, with such communities including Pond Inlet (Mittimatalik), Clyde River (Kangiqtugaapik), Qikiqtarjuaq, and Pangnirtung. These communities are being affected by increased vessel traffic, particularly in terms of disruptions to practices like subsistence hunting, fishing, and gathering, and should be considered in the decision-making processes involved in designing a shipping corridor (van Luijk et al., 2022). Efforts and research towards the inclusion of community input in the development of shipping corridors have been done (and are currently being done), such as Dawson et al. (2020). Such work, however, has not included every community along the eastern coast of Baffin Island.

While much of the vessel traffic is passing through the study area via the Northwest Passage, there is also considerable traffic travelling to and from ports supporting the natural resource extraction industry. One of the largest of these ports supports the Mary River Mine, an open pit iron mine that shipped 6.1 million tonnes of iron ore from Milne Inlet in the 2023 shipping season (Baffinland Iron Mines Corporation, 2024). Mineral extraction is a foundation of Nunavut's economy; the Canadian Government projected that in 2019 the value of Nunavut's mineral production was $1,315 million (Government of Canada, 2021). Any proposed shipping corridor should aim to support the sustainable development of the natural resource sector of Baffin Bay and Davis Strait.

The region being examined in this study currently implements a few localized vessel management actions such as vessel slowdown areas (e.g. Baffinland vessels in Eclipse Sound [Baffinland Iron Mines Corporation, 2024]), avoidance areas (e.g. Ninginganiq National Wildlife

Area [Wildlife Area Regulations, 2023]), and protected migratory bird sanctuaries (e.g. Bylot Island Migratory Bird Sanctuary) which act as avoidance areas due to entry and usage restrictions (Migratory Bird Sanctuary Regulations, 2023). Additionally, a proposed shipping corridor already exists for the study area of Davis Strait and Baffin Bay, however this corridor was not developed with marine mammal conservation as a primary objective (Chénier et al., 2017). The Northern Marine Transportation Corridor (NMTC) described by Chénier et al. (2017), often referred to as a low-impact shipping corridor, was developed with the intention of providing a safe route, with low environmental and social impact, for navigation through the Canadian Arctic. However, due to a lack of available data, the existing corridor was not able to account for marine mammal populations and community input was not solicited in its design. Instead, the primary focus of the corridor is the safe navigability of vessels. To ensure that sustainability objectives are more comprehensively captured, there is a need for further development of the NMTC to include ecological and socioeconomic inputs (Chénier et al., 2017).

The Canadian Arctic represents a unique opportunity for conservation, as it is one of the few developing regions on earth that remains mostly untouched by human activity. Proactive implementation of vessel management solutions that account for ecological and local socioeconomic factors and benefits can provide an example of how sustainable development is both achievable and mutually beneficial for all stakeholders. The disproportionately high impacts of climate change that the Canadian Arctic is experiencing paired with the sensitivity of native species demands that conservation methods are adopted as soon as possible to preserve the region’s unique ecosystem.

This thesis examines the potential of developing a new route for the shipping corridor running through Davis Strait and Baffin Bay as a vessel management strategy that attempts to minimize impacts of vessels on marine mammals. Designing and implementing a shipping corridor was chosen as the preferred vessel management strategy largely due to the ease of combining said corridor with other management strategies. Developing a management strategy that incorporates multiple measures has the potential to be more effective than a strategy that relies solely on a single measure (Halliday et al., 2018). The shipping corridor designed in this study will use speed restrictions in areas of high cetacean densities that cannot be reasonably navigated around. The proposed shipping corridor is based on an analysis of vessel and marine mammal satellite data. The marine mammals being examined in this study are as follows: bowhead whales, beluga, narwhal, sperm whales, killer whales, and northern bottlenose whales. The methods designed and used in this study are easily repeatable and applicable to other regions around the globe, and the research approach can be adapted to a variety of marine wildlife and vessel contexts to support marine conservation efforts in areas around the world.

1.1 Research Purpose and Objectives

The goal of this study is to provide insight into how to address the increasing vessel traffic in the Canadian waters of Davis Strait and Baffin Bay, while ensuring marine mammals and biodiversity are adequately protected. Outcomes from this study contribute to research and scholarship on improving conservation of marine mammals around the world. In addition, the results found through this research could be used in conjunction with existing literature to inform the sustainable development of the Canadian Arctic.

This study aims to answer the following question: How can spatial patterns of marine mammals and vessels be analyzed to inform the establishment of shipping corridors that minimize impacts on marine mammals? This study will attempt to answer this question through the objectives listed below:

1) Evaluate historical vessel traffic and marine species location data for trends.
2) Spatialize and quantify the overlap between each marine species and vessel position data through time.
3) Create a collection of overlap hotspot maps between marine species and vessel traffic for each ice-free month.
4) Determine how to place a shipping corridor through the region, with the aim being to develop a route that avoids monthly hotspots for each species.
5) Analyse how the proposed low-impact shipping corridor differs from the existing corridor.

The objectives are addressed sequentially in different research stages that progressively build on the previous work to produce a final outcome that addresses the research question. The analysis informs the development of a potential low-impact shipping corridor for vessels to travel through the Canadian waters of Davis Strait and Baffin Bay, using overlap with marine mammals as a vector for impact assessment.

2. Methods

2.1. Research Design

The methodology of this study follows an approach similar to that in Halliday et al. (2018, 2022), with alterations made to fit a scope feasible for a master's thesis. The spatial analysis software used in this study was ArcGIS 10.8.2 (ESRI). Due to the scope of this study and the availability of vessel data, two representative years (2016/2019) were selected for vessel AIS data. These two years were selected as representative years of typical shipping years, as 2018 demonstrated uncharacteristically low vessel traffic, and the effects of the COVID-19 pandemic in 2020 led to an atypical reduction in vessel traffic.

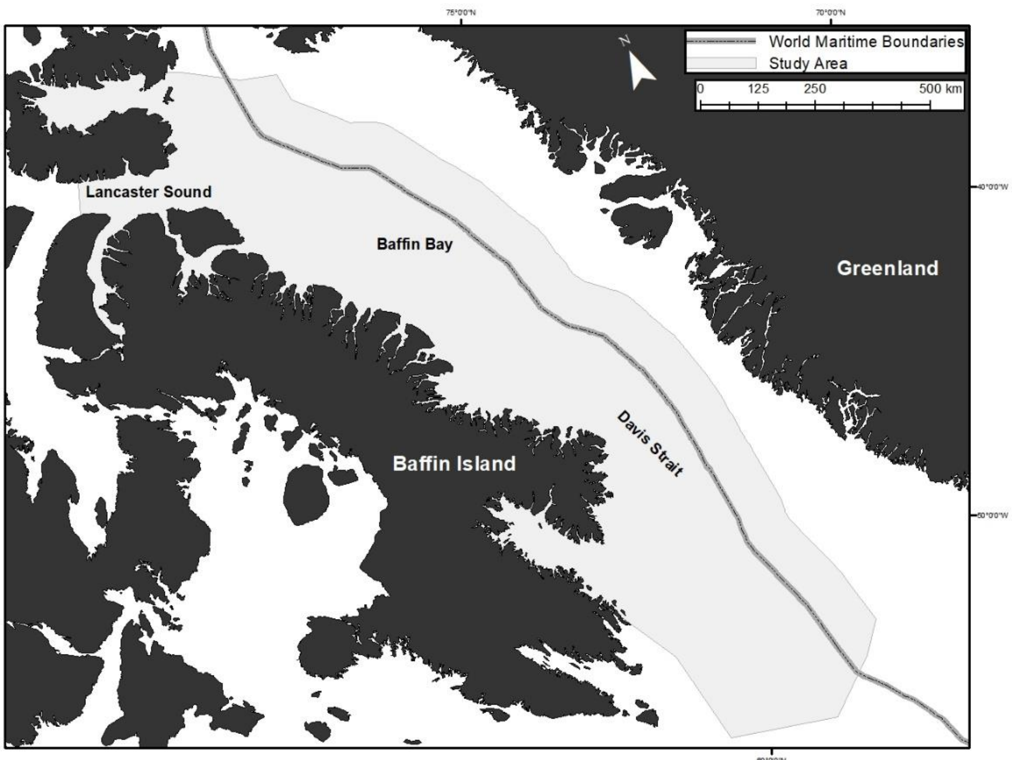
The vessel data were processed into rasters denoting vessel density for each study year, and the marine mammal data were processed to produce monthly density hotspots for different species. These density data were examined to identify trends in shipping and marine mammal activity over time. An overlay analysis was performed on the density data to understand how current shipping traffic is overlapping with marine mammal distributions. A hotspot analysis was then conducted on the overlap between vessel and marine mammal densities following a procedure similar to that in Yurkowski et al. (2019). The results of these analyses were used to develop a single shipping corridor that aims to reduce the impact of increasing vessel traffic on marine mammals throughout the year. The proposed shipping corridor will aim to encompass the best-interests of all parties involved by considering the ecological and socioeconomic implications of implementing the corridor in the Canadian waters of Baffin Bay and Davis Strait.

2.2. Study Area

This research analyzes vessel and marine mammal data collected from Baffin Bay and Davis Strait, Canada. The study area follows the Northwest Passage as it travels along the eastern coast of Baffin Island and enters Lancaster Sound. The area ranges longitudinally from the Canada-Greenland marine boundary at the south of Davis Strait (55^{o}22’6”W) to Lancaster Sound (86^{o}55’14”W) and latitudinally from the southern tip of Baffin Island (59^{o}53’13”N) to the southern end of Ellesmere Island (76^{o}25’6”N) (Figure 1).

Figure 1

Map of the study area, consisting of the Canadian waters of Baffin Bay and Davis Strait.



2.3 Vessel data

The vessel data were compiled from satellite Automatic Identification System (AIS) data (Spire Global, Cambridge, ON). These data were translated into vessel tracks using a least cost approach for each individual vessel , creating track lines along the shortest route between consecutive points while accounting for land. While all classes of vessels were included, the AIS data collected represent a subset of the actual vessel traffic, since AIS transponders are not mandatory on all vessel classes, some vessels have AIS transponders turned off at times, and satellite coverage can sometimes be limited which can lead to gaps in the data (Halliday et al., 2018). The vessel tracks were converted into 10km rasters that represent the total number of vessel tracks that traveled through the cell for each month throughout the study period (July-December, 2016/2019), denoting which areas experience the most vessel traffic (Dawson et al., 2018; Halliday et al., 2022).

2.4. Marine mammal data

2.4.1. Satellite telemetry data

The marine mammal data used in this paper were obtained from existing satellite telemetry data from Fisheries and Oceans Canada (DFO), as well as Greenland Institute of Natural Resources for an additional bowhead whale dataset. The dataset consists of telemetry data collected from 1992 to 2022 for 433 individuals across six cetacean species (bowhead whales *Balaena mysticetus*, beluga *Delphinapterus leucas*, narwhal *Monodon monoceros*, sperm whales *Physeter macrocephalus*, killer whales *Orcinus orca*, and northern bottlenose whales *Hyperoodon ampullatus)* (Table 1). The number of observed days and tagged individuals are included in Table 1 along with the average number of days per individual whale in the dataset. These numbers represent an estimate of sampling effort between species. Details of the capture and tagging methods for these species are described in (Breed et al., 2017; Dietz et al., 2008; Ferguson et al., 2010; Feyrer et al., 2024; Lefort et al., 2022; Richard et al., 2001; Shuert et al., 2021; Watt et al., 2016).

The satellite-relay dataloggers all used the ARGOS geolocation system to produce a minimum of one location per day. To account for the high volume of spatial data and positional errors in the ARGOS dataset (0.3-36km; Costa et al., 2010), a discrete-time correlated random walk-through hierarchical state-space model (Jonsen, 2016, Jonsen et al., 2005) was used to develop a set of standardized daily position data for each individual. A more comprehensive description of the methods above can be found in Yurkowski et al. (2019).

2.4.2. Marine mammal density

To estimate monthly relative densities for each species of marine mammal, kernel densities were calculated for each month (July-December) using the standardized daily position data developed above. The kernel densities were created in R using the ‘ks’ Package Version 1.11.5 (Duong, 2019) and the standard smoother cross-validation bandwidth selector. The resulting kernel density rasters were imported into ArcGIS 10.8.2 and resampled from the native 1m resolution to a 10km resolution raster to create data layers of the same cell size as the marine vessel data layers. Standardizing the position data to a single point per day reduced the disproportionate effects of individuals and outlier data on the results. A more detailed description of these methods can be found for bowheads in Halliday et al. (2022).

Table 1. Description of the species datasets used in this study.

Dataset	**Tracking Period**	**Monthly Range**	***N* Months**	***N* Individuals**	***N* Days**	**Average Days**	**At Risk Status**
Narwhal	1997-2000, 2003-2012, 2006-2007	July-December	6	148	8664	58.54	COSEWIC: Not at Risk
Northern Bottlenose Whale (Davis Strait-Baffin Bay-Labrador Sea)	2019, 2021	July-December	6	20	568	28.40	COSEWIC: Special Concern SARA: Under Consideration
Sperm Whale	2018, 2019	September-November	3	5	145	29.00	COSEWIC: Not at Risk
Beluga (High Arctic)	1998-2000, 2006-2009	July-December	6	28	1603	57.25	COSEWIC: Special Concern SARA: Under Consideration
Beluga (Cumberland Sound)	1992-1993, 2002-2005, 2006-2008, 2012-2013, 2015	July-December	6	19	1223	64.37	COSEWIC: Endangered SARA: Threatened

Bowhead (Eastern Canada-West Greenland)	2006-2007, 2011-2015, 2012-2014	July-December	6	209	20144	96.38	COSEWIC: Special Concern SARA: Under Consideration
Killer Whale	2009	August-October	3	4	119	29.75	COSEWIC: Special Concern SARA: Under Consideration

2.5. Data analysis

All data were grouped into months ranging from July-December to understand how both marine mammals and vessels traveled through the study area as the waters transition from the ice-free period in the summer (July-September) to the periods with increasing concentrations of sea ice (November-December). Due to the lower-availability of data, marine mammal data were collected for a large range of years (1992-2022) to ensure the position data were more representative of actual populations. Vessel data were readily available from the AIS database, allowing for the selection of 2016 and 2019 as two years that were representative of modern shipping traffic through the study area, while also allowing for a comparison of how increasing vessel traffic is overlapping with the marine mammal populations.

2.5.1. Overlay analysis

The vessel raster data were used in conjunction with the marine mammal monthly density data to understand how each species overlaps with vessel traffic. An overlay analysis was conducted in ArcGIS 10.8.2 to identify where the activities of different species intersect with vessels in each 10km grid cell on a monthly basis for both study years (a total of 74 maps were produced). To determine the risk of overlap between vessel traffic and marine mammals, the vessel traffic intensity was multiplied by each species' density. The overlap risk values were then normalized by the maximum observed overlap risk value to obtain new risk values between 0 and 1. These new risk values denote areas where overlap ranges from 0 (i.e. either no vessels or no marine mammals were observed, or both) to 1 (i.e. a cell in which the maximum values for both vessel traffic and marine mammal density were observed). Normalizing these overlap risk values allowed for the comparison of how overlap risk differed both throughout the studied months and between species.

Observations of the resulting overlap maps were recorded, examining how overlap risk changes throughout the year for each species. The results of these analyses identified areas that demonstrated increased levels of overlap between vessels and marine mammals, that were then used as metrics in further analyses. Conducting these analyses for both 2016 and 2019 revealed how vessel impacts on marine mammals had changed over time.

2.5.2. Hotspot analysis

The methods used to derive an overlap hotspot map are described in Yurkowski et al. (2019). The Hotspot Analysis tool in ArcGIS 10.8.2 and the Getis-Ord Gi statistic were used. The results from the 2019 overlap analyses conducted in this study were used as the input for this method, allowing for a statistical analysis of what areas should or should not be considered hotspots for overlap risk between vessel traffic and marine mammals.

The Hotspot Analysis tool calculates a Getis-Ord Gi statistic, determining for each 10km cell the likelihood that is located within a hotspot for, in our case, overlap risk. The Getis-Ord Gi statistical test results in z-scores for each feature that range in value from -3 to +3, as well as p-values to show the statistical significance of the analyses for each of the features. Positive z-score values indicate hotspots, whereas negative z-score values indicate coldspots. The z-scores values correspond to statistical significances with 3 being high significance (i.e., p=0.01), 2 being moderate significance (i.e., p=0.05), 1 being weak significance (i.e., p=0.1), and 0 being not significant. For this study, cells with a z-score value of 2 or 3 were considered hotspots. This analysis also allowed for the creation of visual representations of current high-risk areas for each species depending on the month in the form of a hotspot map. The hotspot map indicates areas that have demonstrated high incidence of overlap between vessels and marine mammals in the Canadian waters of Baffin Bay and Davis Strait.

A hotspot analyses was conducted for each species. Then, the data layers for each species were merged, and the z-score values were summed to create an aggregate hotspot map for each month. Note that only cells with a hotspot value of 2 or greater were included in this data merge, resulting in an output raster layer where each 10km cell either was defined in a binary manner, as either a hotspot or not a hotspot. The resulting binary hotspot map consisted of 10km cells containing a value of 1 or 0, indicating whether they were considered a hotspot or not a hotspot, respectively. The binary hotspot cells for each species were then added together, producing cells with a value ranging from 0 to 7. The resulting maps indicate areas that were overlap hotspots for both individual and multiple species, where a value of 0 indicates a cell was not an overlap hotspot for any species that month, with values increasing based on the number of species a cell would be considered a hotspot for overlap (e.g. a value of 1 is an overlap hotspot for a single species, a value of 7 is an overlap hotspot for all considered species).

The visual representation of overlap hotspots can be easily understood by various audiences that may need to be addressed in the implementation of a shipping corridor. The current NMTC was also overlaid with the hotspot map to examine where it intersects areas of high overlap between marine mammals and vessel traffic, as well as how it compares to the low-impact corridor developed in this paper.

2.5.3. Shipping corridor placement

To begin developing a shipping corridor, the data that would best inform a shipping corridor that minimizes impacts on marine mammals was assessed. While much of the efforts in the earlier stages of this study had been towards quantifying the impacts of current vessel traffic on marine mammals, these analyses did not adequately identify the best placement of such a corridor. The issue with using these data to inform a low impact shipping corridor is that these maps do not show areas with high marine mammal density independent of vessel traffic. Due to this limitation, using these maps for such a corridor could result in higher impact in previously low impact areas. Therefore, the optimal data to base a shipping corridor that minimizes impacts on marine mammals was determined to be the marine mammal density data.

To produce a low impact shipping corridor that was effective for each month, the density data across all species of marine mammals were summed to create a single dataset indicating areas of high marine mammal density for each month. All months were then layered onto a map of the study area to indicate regions that did not experience high marine mammal density at any point throughout the shipping season. A shipping corridor was then able to be developed that prioritised avoiding the areas of high marine mammal density while attempting to remain as spatially aligned with the existing NMTC as possible. Once a corridor was developed, the total distance required to travel from Davis Strait to Lancaster Sound was measured for both the existing NMTC and the newly developed low-impact corridor. This measurement was used to provide a sense of the differences in cost and convenience for vessels following the implementation of the new corridor with the assumption that increased travel distance would result in increase costs to vessel operators.

3. Results

3.1. Vessel traffic

When examining vessel traffic of all classes, both years (2016 and 2019) exhibited similar seasonal patterns. Vessel traffic levels rise significantly in July before peaking in August and decreasing until the end of the year, with the minimum levels being observed in December. Vessel traffic density in 2016 per 10km cell ranged from 0 to 128, exhibiting a mean raster value of 0.810 (vessels per 10km cell) over the whole season (July - December), with a minimum monthly mean raster value of 0.101 in December and a maximum monthly mean value of 1.97 in August. Vessel traffic density per 10km cell in 2019 ranged from 0 to 277, exhibiting a mean raster value of 1.24 over the whole season, with a minimum monthly mean raster value of 0.094 in December and a maximum monthly mean value of 3.07 in August. These values indicate a 53% increase in mean vessel traffic and a 55% increase in peak vessel traffic from 2016 to 2019. A summary of the vessel density results for both years is provided in Table 2. A spatial comparison of vessel density between August 2016 and August 2019 is provided in Figure 2.

Table 2. Summary of vessel traffic in 2016 and 2019.

				2016			
	Yearly	**July**	**August**	**September**	**October**	**November**	**December**
Mean	0.810	0.680	1.974	1.385	0.586	0.132	0.101
Max	52.833	27	117	128	27	7	11
Min	0	0	0	0	0	0	0
				2019			
	Yearly	**July**	**August**	**September**	**October**	**November**	**December**
Mean	1.242	1.051	3.070	2.127	0.882	0.228	0.094
Max	130.167	91	277	250	135	13	15
Min	0	0	0	0	0	0	0

Figure 2

Vessel density maps of the study area, comparing (a) August 2016 and (b) August 2019.

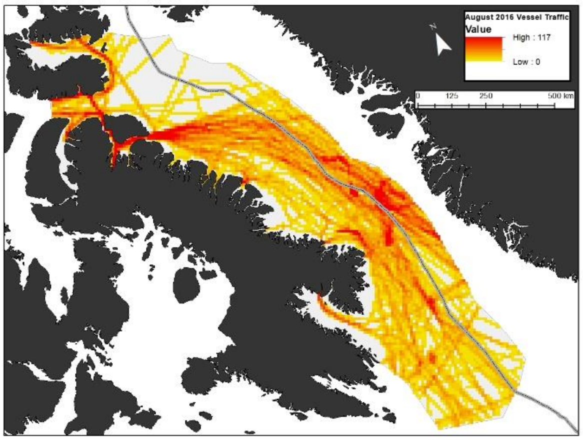


Figure 2-a

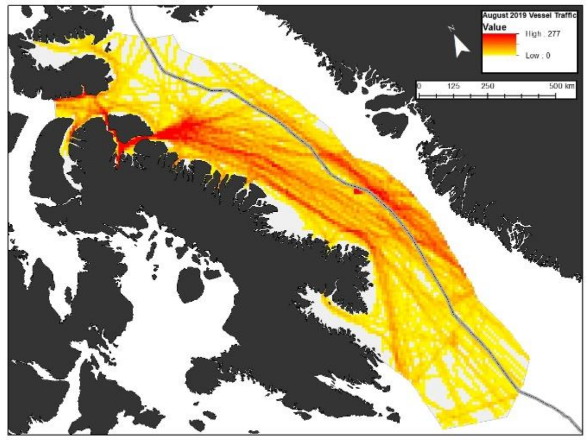


Figure 2-b

3.2. Marine mammal distribution

The monthly marine mammal density rasters allowed an assessment of the spatial and temporal trends of each species within the study area throughout the shipping season. The patterns are described below.

3.2.1. Narwhal

Position data for narwhal were available from July-December. In July, narwhal presence in the study area concentrated in the southern half of Lancaster Sound, extending into Admiralty Inlet and the northern entrance to Eclipse Sound. In August, the narwhal moved further into Admiralty Inlet and Eclipse Sound, away from Lancaster Sound. The narwhal spread throughout Admiralty Inlet and Eclipse Sound in September, with the Eclipse Sound group favouring the eastern channel of Eclipse Sound over the northern channel. In October, the narwhal spread out among the entire eastern coast of Baffin Island north of Cape Dyer, as well as much of Lancaster Sound. November saw the narwhal populations move away from shore, 170 km east of Qikiqtarjuaq. This offshore location is known as the Disko Fan Conservation Area (DFCA), a marine refuge area with a fisheries closure aiming to preserve coral concentrations and protect winter narwhal habitat. The narwhal distribution remained focused on the DFCA in December, however there are lower densities spreading north and south of the feeding area.

3.2.2. Northern Bottlenose Whale

Position data for northern bottlenose whales were available from July-December. Northern bottlenose whale distribution in July exhibited a spread-out pattern suggesting migratory behaviour from the southeastern corner of the study area, extending up to Cape Dyer. In August, this migratory distribution pattern moved further southeast, with only a fringe of the distribution entering the southeastern corner of the study area. The September distribution moved into the study area, focusing the highest density on the DFCA, with lower densities radiating throughout much of the study area south of Clyde River. In October, the distribution of northern bottlenose whales was far more condensed than in September, forming a narrow pattern running along the Canada-Greenland maritime border at the DFCA. In November, the northern bottlenose whale distribution exhibited a migratory pattern ranging from 72^{o}56’N to the southeastern corner of the study area. The highest density in November was still around the DFCA. By December, the majority of the distribution of northern bottlenose whales had left the study area, with the edges of the distribution entering the southeast edge of the study area.

3.2.3. Sperm Whale

Position data for sperm whales were available from September-December. In September, sperm whale density was focused in a small area inside the DFCA. The sperm whales remained along the DFCA in October, however the distribution was more spread out than September, exhibiting a narrow north-south migratory pattern. By November, most of the sperm whales had left the study area, traveling south, with only a low density of sperm whales remaining in the southern extent of the study area. In December, there were no remaining sperm whales in the study area.

3.2.4. Beluga – High Arctic Population

Position data for the High Arctic population of belugas were available from July-December, however the population did not enter the study area until September, entering from the west through Lancaster Sound. In September, the distribution of High Arctic belugas was shown to line the coast of Devon Island, extending through Lancaster Sound and entering Jones Sound. The October distribution occupied Jones Sound, the northern half of Lancaster Sound, and extended north from Jones Sound, out of the study area. In November, the High Arctic belugas had moved out of Lancaster Sound, with lower densities in Jones Sound and higher densities just north of the entrance to Jones Sound, outside of the study area. By December, the High Arctic population had migrated from Jones Sound and the surrounding area over to the west coast of Greenland, with the edge of the distribution intersecting with the eastern edge of the study area at around 68^{o}N.

3.2.5. Beluga – Cumberland Sound Population

Position data for the Cumberland Sound population of belugas were available from July-December. As the name suggests, this population of belugas remained in Cumberland Sound throughout the examined months. In July, the belugas were largely condensed in Clearwater Fiord, a fjord located in the northern reaches of Cumberland Sound; however, lower densities were present further out into the north end of Cumberland Sound. In August, the belugas retreated almost entirely into Clearwater Fiord. By September, the population had moved further out into the main body of Cumberland Sound; however, there remained a high density of belugas in Clearwater Fiord. In October and November, the population of belugas had left Clearwater Fiord and occupied the main body of Cumberland Sound. In December, the population of belugas had moved to the entrance of Cumberland Sound, lining the northern shore.

3.2.6. Bowhead Whale

Position data for bowhead whales were available from July-December. In July the bowheads were distributed throughout most of the Canadian waters of the study area north of, and including, Cumberland Sound. The highest density of bowheads during this time was found offshore from Clyde River. In August, the bowheads were far less spread out, consisting of two main groups with lower density offshoots. A lower density group was located in Cumberland Sound, while the highest density of bowheads in August could be found in and around Ninginganiq National Wildlife Area (NWA), a protected area created to provide safe habitat for these bowhead whales. In September, the bowheads were still in Cumberland Sound and Ninginganiq NWA, occupying distributions that were consistent with those observed in August. By October, the Ninginganiq NWA group of bowheads had begun transitioning south, being distributed along the coast near Qikiqtarjuaq. The Cumberland Sound group remained in Cumberland Sound but had spread out. In November, bowheads were distributed along the entire coast of Baffin Island within the study area, with higher densities being found near Qikiqtarjuaq and the southeastern end of Cumberland Sound. By December, the distribution of bowheads had decreased from the earlier months, with most bowheads being distributed around the entrance to Cumberland Sound or just southwest of the study area, as well as a small group near Qikiqtarjuaq.

3.2.7. Killer Whale

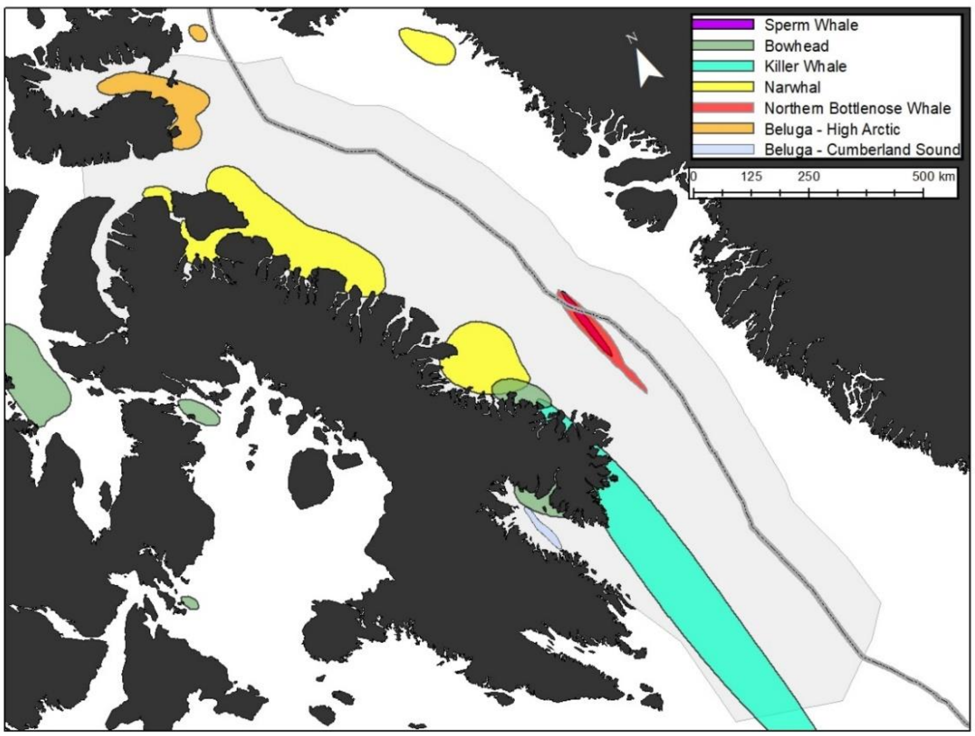
Position data for killer whales were available from August-October. In August, the highest density of killer whales was found throughout the length of Admiralty Inlet, extending into Lancaster Sound, with a lower density present along the northern channel of Eclipse Sound. In September, the distribution of killer whales was highest along the coast of Baffin Island between Clyde River and Eclipse Sound, however lower densities radiated from this point throughout the northern half of the study area. By October, the killer whales had begun exhibiting a migratory distribution pattern running north-south along the entirety of Baffin Bay and Davis Strait as they migrated south.

3.2.8. Utilization Distribution

Using the marine mammal distribution rasters, polygon shapefiles were developed representing areas that exhibited a >50% utilization for each species over each month. The 50% utilization distribution shapefiles represented areas that the subject species was present in for at least half of the days in that month. This allowed for the production of a visual representation of monthly high-use areas for each species; an example of such a visual is provided in Figure 3.

Figure 3

Map of the study area depicting the October 50% utilization distribution of marine mammals based on kernel density data.



3.3. Vessel exposure to marine mammals

3.3.1. Narwhal

Comparing both study years, 2016 and 2019, overlap between narwhal and vessel traffic shared similar spatial patterns. The highest overlap risk occurred during the months of August to

September, when sea ice extent is lowest, and the overlap was localized around the eastern entrance to Eclipse Sound. In October, the overlap risk transitioned south out of Eclipse Sound into Baffin Bay, continuing further south into Davis Strait in November and December. While the spatial distribution of narwhal-vessel traffic overlap was similar, the magnitude of the overlap risk differed between the study years. The mean raster value of risk of overlap between narwhal and vessel traffic increased from 0.000164 in 2016 to 0.000317 in 2019, a 92.7% increase. The difference in peak overlap risk values, 0.223 in August 2016 and 0.526 in August 2019, represented an increase of 137%.

3.3.2. Northern Bottlenose Whale

When comparing results for 2016 and 2019, the spatial distributions of overlap risk between northern bottlenose whales and vessel traffic were similar. In both years, overlap risk began low in July and decreased in August, and it was centred on an area approximately 250 km offshore from the entrance to Cumberland Sound. In September, the mean overlap risk increased by a factor of >10 times, with the area of high overlap risk covering the majority of the study area between latitudes 70^{o}N and 64^{o}N. The mean overlap risk values in October returned to levels comparable with values found in August of the same year, localized along a narrow swath running from latitudes 69^{o}N to 66^{o}N along the Canada-Greenland Maritime Border. In November, the mean overlap risk value remained low; however, the spatial distribution was far more spread out, with scattered higher-overlap areas being found offshore south of 70^{o}N. December of both years demonstrated the lowest overlap risk by far, two orders of magnitude lower than November, with the only cells expressing overlap risk being found on the southern border of the study area. The mean raster value of risk of overlap between northern bottlenose whales and vessel traffic increased from 0.000451 in 2016 to 0.000636 in 2019, a 40.7% increase. The max overlap risk values for both years were the same, 0.0704 in both September 2016 and September 2019.

3.3.3. Sperm Whale

The risk of overlap with vessel traffic was examined for sperm whales during a three-month period running from September to November, as these were the months that sperm whales were present within the study area. The spatial pattern of overlap risk between sperm whales and vessel traffic remained consistent between the two study years of 2016 and 2019. Mean overlap risk was highest during September, focused in a small (~25 cells) area that is approximately 225 km offshore, northeast of Cape Dyer on Baffin Island. Overlap risk decreased significantly in October, though the spread of areas expressing overlap risk increased, while still being centred on the high-overlap area identified in September data. The November data showed the lowest mean overlap risk of the three months, with instances of overlap being identified offshore, south of Cumberland Sound, through sparse vessel track lines. Contrary to other species being studied, the mean raster value of risk of overlap between sperm whales and vessel traffic decreased from 0.00103 in 2016 to 0.000843 in 2019, an 18.1% decrease. The max overlap risk values also decreased from 0.0634 in October 2016 to 0.0387 in October 2019, a decrease of 38.9%.

3.3.4. Beluga – High Arctic Population

The High Arctic population of belugas were only present in the study area from September-December, leading to the only risk of overlap High Arctic belugas and vessel traffic in the study area occurring during this period. Following similar spatial patterns across 2016 and 2019, overlap risk was found to be high in September, lining the southeast coast of Devon Island and the eastern entrance to Jones Sound. October and November both exhibited far lower overlap risk, with areas of risk being located closer to Greenland in both months, and along the southern side of Lancaster Sound in October only. December mean overlap risk values were the highest of the four months; however, the location of the overlap had transitioned further south, between the latitudes 70^{o}N to 66^{o}N in the Greenlandic waters of Baffin Bay and Davis Strait. The mean raster value of risk of overlap between High Arctic belugas and vessel traffic increased from 0.0000182 in 2016 to 0.0000395 in 2019, a 117.2% increase. The difference in peak overlap risk values, 0.00767 in September 2016 and 0.0143 in September 2019, represented an increase of 85.9%.

3.3.5. Beluga – Cumberland Sound Population

While the Cumberland Sound population of Belugas was present in the study area for all examined months, the lack of vessel traffic in certain months resulted in no overlap risk for a portion of the study period. Vessels traveled through Cumberland Sound in order to reach the community of Pangnirtung, following a direct route that resulted in a low spread of vessel traffic in the area. When comparing 2016 and 2019, the pattern of overlap risk differed at times between the years. Both years demonstrated no overlap risk through July and August when the beluga population remained in Clearwater Fiord, deep in Cumberland Sound. September saw the beluga population leave Clearwater Fiord and begin to intersect with the supply route to Pangnirtung, resulting in a low risk of overlap for both 2016 and 2019.

In October, the risk of overlap increased considerably for both years as the beluga population transitioned towards the entrance of Cumberland Sound, intersecting more with the supply route. During November was when the pattern of overlap risk differs, with 2016 data showing risk of overlap between the Cumberland Sound population of belugas and vessel traffic while 2019 expressed no risk of overlap. December of both years experienced no risk of overlap, as vessels were no longer traveling through Cumberland Sound. The mean raster value of risk of overlap between Cumberland Sound belugas and vessel traffic increased from 0.0000188 in 2016 to 0.0000293 in 2019, a 55.9% increase. The difference in peak overlap risk values, 0.00636 in November 2016 and 0.00784 in September 2019, represented an increase of 23.3%.

3.3.6. Bowhead Whale

Overlap risk between bowhead whales and vessel traffic in the study area remained spatially consistent between 2016 and 2019, barring a few minor exceptions. However, the magnitude of overlap risk increased from 2016 to 2019. In July, much of the study area expressed risk of overlap, with higher levels of overlap being found along the Pangnirtung supply route in Cumberland Sound, and a ~175 km stretch of water lining the east coast of Baffin Island from Eclipse Sound to Qikiqtarjuaq. Additionally, in 2016, there was risk of overlap found at the entrance of Admiralty Inlet, south of Lancaster Sound. In August, the risk of overlap was at the highest levels of the year and was present in the majority of the study area, with the only areas exhibiting zero risk of overlap being north of Lancaster Sound and parts of Cumberland Sound (Figure 4).

Figure 4

Maps of the study area depicting overlap risk between bowheads and vessel traffic in (a) August 2016 and (b) August 2019.

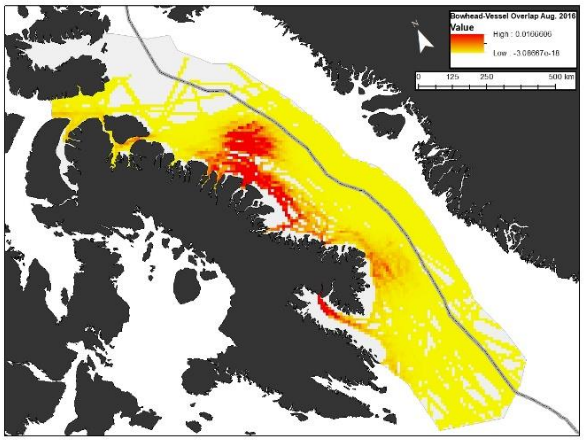


Figure 4-a

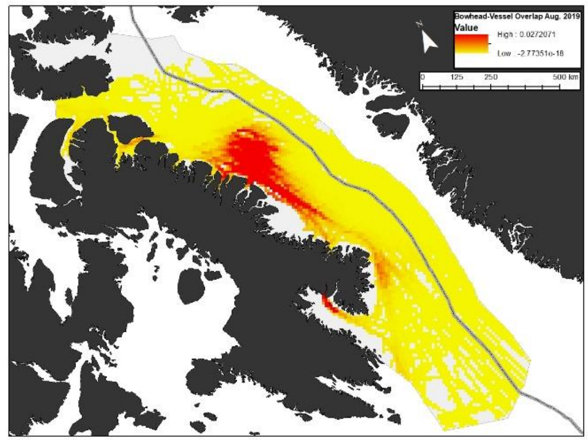


Figure 4-b

Overlap risk in August was highest in an area offshore from Clyde River that extended south along the coast. The supply route into Pangnirtung also demonstrated higher overlap risk. Overlap risk in September was lower than in August but is still expressed in much of the study area. There was a higher incidence of overlap risk in the waters in and around Ninginganiq NWA, south of Clyde River. Mean overlap risk was similar in September and October; however, in October, the areas expressing higher overlap risk were further south. These areas were the waters surrounding Qikiqtarjuaq and along the supply route into Pangnirtung. November and December both expressed far lower levels of overlap risk, with the areas of overlap risk being located towards the southern extent of the study area, as ships travelled in and out of both

Hudson Strait and the Labrador Sea. The mean raster value of risk of overlap between bowhead whales and vessel traffic increased from 0.0000546 in 2016 to 0.000115 in 2019, a 111.2% increase. The difference in peak overlap risk values, 0.0174 in October 2016 and 0.0523 in October 2019, represented an increase of 200.0%.

3.3.7. Killer Whale

Killer whales were present in the study area for three months from August to October. The spatial pattern of overlap risk was similar across the two study years, 2016 and 2019. In August, the areas exhibiting a risk of overlap were found in Lancaster Sound, Admiralty Inlet, and Eclipse Sound. In September, the mean overlap risk increased to the peak of the three-month period. The areas showing overlap risk in August continued to express risk into September; however, higher incidences of risk were found in an area extending ~100 km from the eastern entrance to Eclipse Sound, extending south to Clyde River. There was also higher risk in fjords along this span, particularly in Scott Inlet and Kangiqtualuk Uqquqti.

October exhibited a mean overlap risk similar to levels in August; however, the areas exhibiting risk were far more spread out. The higher risk areas followed the migratory path of the killer whales as they travelled along the coast of Baffin Island south from Clyde River towards the Labrador Sea. During this migration, there was also higher risk along the Pangnirtung supply route. The mean raster value of risk of overlap between killer whales and vessel traffic increased from 0.000889 in 2016 to 0.00135 in 2019, a 51.5% increase. The difference in peak overlap risk values, 0.0773 in September 2016 and 0.125 in September 2019, represented an increase of 61.7%.

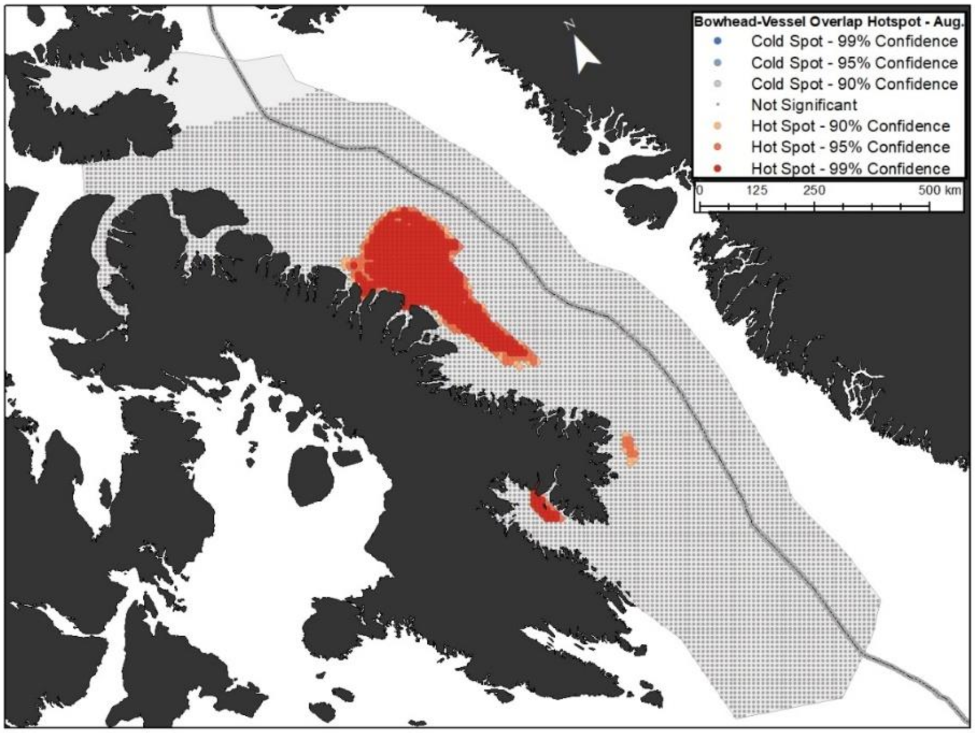
3.4. Hotspots of vessel traffic and marine mammal overlap

3.4.1. Hotspot Analysis

The overlap hotspots were generated using the 2019 overlap risk rasters. A hotspot analysis was conducted for each species and each month, based on available data, that exhibited risk of overlap with vessel traffic, resulting in 37 maps outlining overlap hotspots. Assessing these maps, the areas designated as overlap hotspots aligned with the areas identified in the overlap analysis above as areas of higher risk of overlap. Figure 5 provides an example of an output of a hotspot analysis for bowhead-vessel traffic overlap in August 2019.

Figure 5

Hotspot map of bowhead and vessel traffic overlap in August 2019.



3.4.2. Monthly Hotspots

The process of aggregating all species hotspots into a single raster for each month produced a map that shows both where all overlap risk hotspots are for a month and whether an area was a hotspot for overlap risk for multiple species. These areas that demonstrate higher overlap risk for multiple species identify areas that could represent higher impact from the vessel traffic present, as the vessels risk overlapping with more than one species. All months produced single- and two-species overlap hotspots, with October being the only month to produce a three-species overlap hotspot as well.

The study area was divided into 7924 10 km grid cells. By dividing the number of grid cells that are considered overlap hotspots by the total number of grid cells in the study area, a percent of the study area that is considered an overlap hotspot was determined for each month. The percent cover of overlap hotspots is provided in Table 2.

Table 3. Percent cover of overlap hotspots for all species in the study area.

	July	**August**	**September**	**October**	**November**	**December**
Percent Cover	12.7%	11.7%	26.0%	20.9%	15.2%	4.7%
Mean Cell Value	0.130	0.122	0.274	0.232	0.173	0.0568

July exhibited a 12.7% overlap hotspot cover of the study area, with a mean raster value of 0.130. A large single-species overlap hotpot was found throughout Eclipse Sound, extending

~175 km from the eastern entrance before continuing south to Clyde River in a ~100 km swath and then narrowing to 30 km until the hotspot ended east of Qikiqtarjuaq. A separate single-species overlap hotspot was located ~250 km east of Cumberland Sound, on the Canada-Greenland maritime border. The supply route into Pangnirtung was also a single-species overlap hotspot in July. A two-species overlap hotspot ran into Eclipse Sound through the eastern entrance.

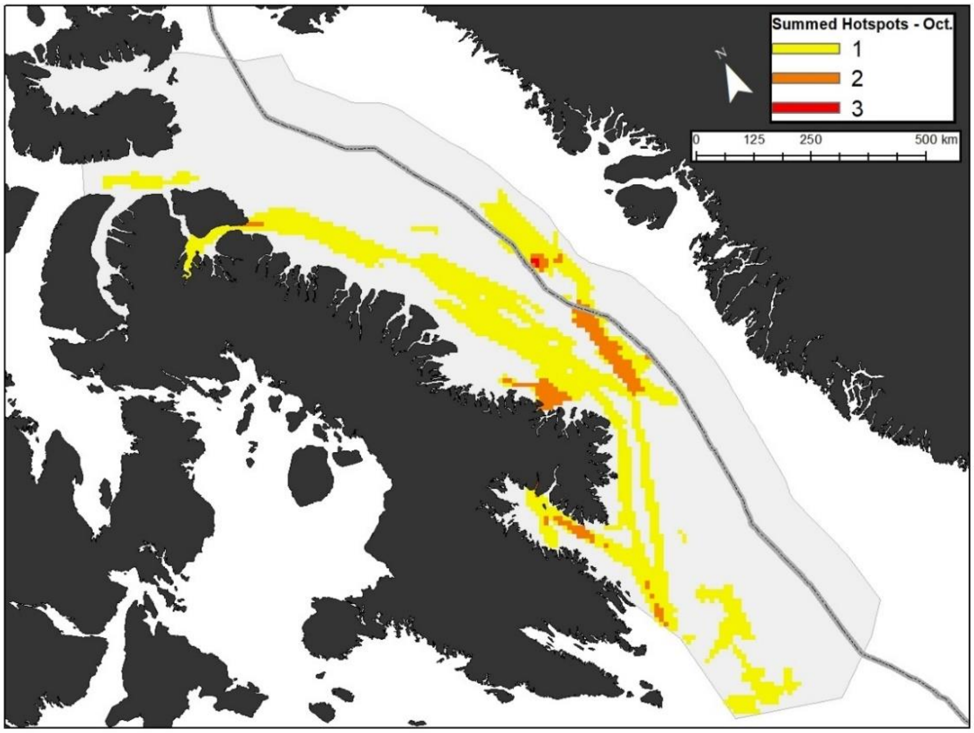
August exhibited an 11.7% overlap hotspot cover, with a mean raster value of 0.122. Single-species overlap hotspots were located entering Admiralty Inlet, in both entrances to Eclipse Sound, in a large area off of Clyde River running south to Qikiqtarjuaq, along the Pangnirtung supply route, and 250 km east of Cape Dyer in Greenlandic waters. A two-species overlap hotspot was located as the two channels of Eclipse Sound converge and enter Milne Inlet.

September exhibited a 26.0% overlap hotspot cover and a mean raster value of 0.274, demonstrating the highest level of overlap risk of any month. Much of the study area south of Eclipse Sound was designated as a single-species overlap hotspot, with one hotspot covering a ~120 km path from latitudes 72^{o}N, near Eclipse Sound, to 68^{o}N. Another large single-species hotspot was located along the Canada-Greenland maritime border, spanning the entire width of the study area east of Cape Dyer running from latitudes 69^{o}N to 65^{o}N, with a narrow path continuing south through Canadian waters to 62^{o}N. The coastline of Devon Island and the entrance to Jones Sound also possessed a single-species overlap hotspot, continuing along the supply route to Grise Fiord. The supply route into Pangnirtung in Cumberland Sound was marked as a single-species overlap hotspot, with a small portion being a two-species overlap hotspot. Other two-species overlap hotspots were located along the eastern channel of Eclipse Sound and into Milne Inlet, southeast of Clyde River, at the Disko Fan Conservation Area (DFCA) and the waters around Dundas Harbour in Lancaster Sound.

October exhibited a 20.9% overlap hotspot cover and a mean raster value of 0.232. October was also the only month to produce a three-species overlap hotspot. A continuous single-species overlap hotspot ran east from Milne Inlet in Eclipse Sound into Baffin Bay and continued along the coast of Baffin Island, approximately 15-50 km offshore, before reaching the southern boundary of the study area. Additional single-species overlap hotspots were located in Cumberland Sound, along the southern half of Lancaster Sound, and along the DFCA. Two-species overlap hotspots were located along the Pangnirtung supply route, exiting the southeast boundary of the study area, along the DFCA, in the waters surrounding Qikiqtarjuaq, and at the eastern entrance to Eclipse Sound. A small (3 10 km cells) area was designated as a three-species overlap hotspot, located at the DFCA. The distribution of the summed overlap hotspots is presented in Figure 6.

Figure 6

Study area map of summed overlap hotspots for all species in October 2019.



November exhibited a 15.2% overlap hotspot cover and a mean raster value of 0.173. The single-species overlap hotspots in November covered most of the width of the study area from Clyde River to Cape Dyer. South of Cape Dyer the single-species overlap hotspots followed headings southwest towards Hudson Strait and southeast into Greenlandic waters. Another single-species overlap hotspot was located at the southernmost extent of the study area. No overlap hotspots were present north of Clyde River. Two-species hotspots were present: offshore from Cape Dyer along the DFCA, and at the southernmost extent of the study area.

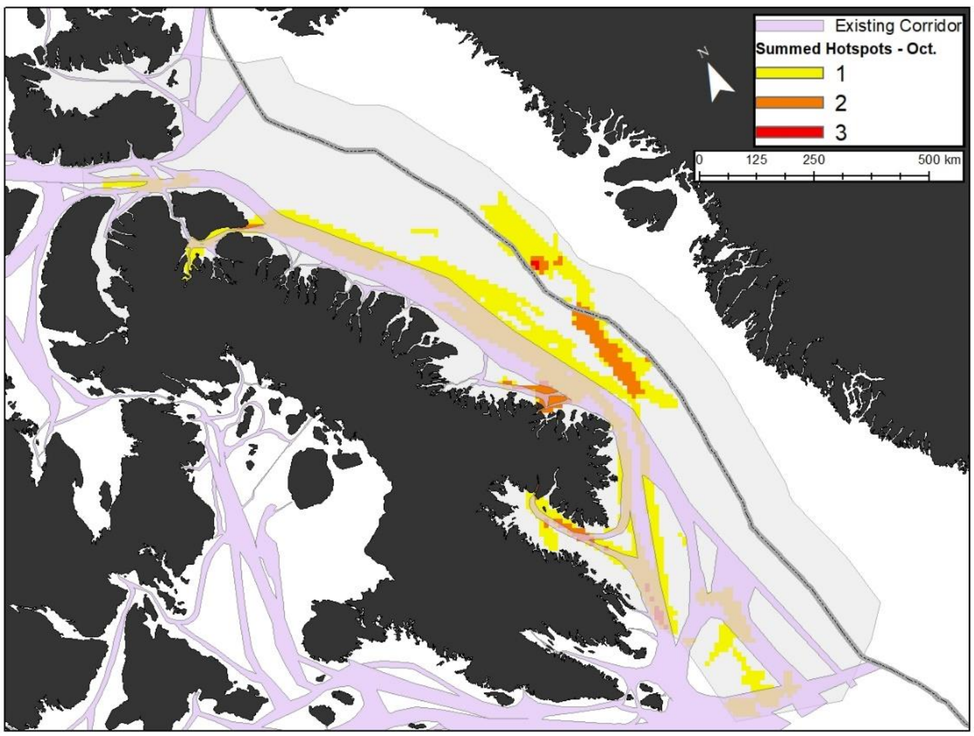
December exhibited a 4.7% overlap hotspot cover and a mean raster value of 0.0568, the lowest presence of overlap hotspots throughout the year. The location of single-species overlap hotspots were in the Greenlandic waters around the DFCA and around the southwestern boundary of the study area. Both of these single-species overlap hotspots contained areas designated as two-species overlap hotspots within their extents.

3.4.3. Assessing the existing corridor

Overlaying the NMTC developed by Chénier et al. (2017) with the summed hotspot rasters demonstrated how the proposed corridor would intersect with areas found to be hotspots for overlap between marine mammals and vessel traffic. To provide an example, Figure 7 illustrates how the NMTC intersects with October overlap hotspots.

Figure 7

Map with the Northern Marine Transportation Corridor (Chénier et al., 2017) overlaid with the summed overlap hotspots for October 2019.



The NMTC passed through several areas that contained overlap hotspots throughout multiple months of the year. Portions of the corridor through narrow passages, such as Eclipse Sound or the supply route to Pangnirtung were areas that consistently intersected with overlap hotspots. Additionally, the primary route that the shipping corridor follows through the study area, running 5-100 km offshore along the east coast of Baffin Island, intersected consistently with hotspots for overlap. This primary route also intersected with overlap hotspots along the southern half of Lancaster Sound.

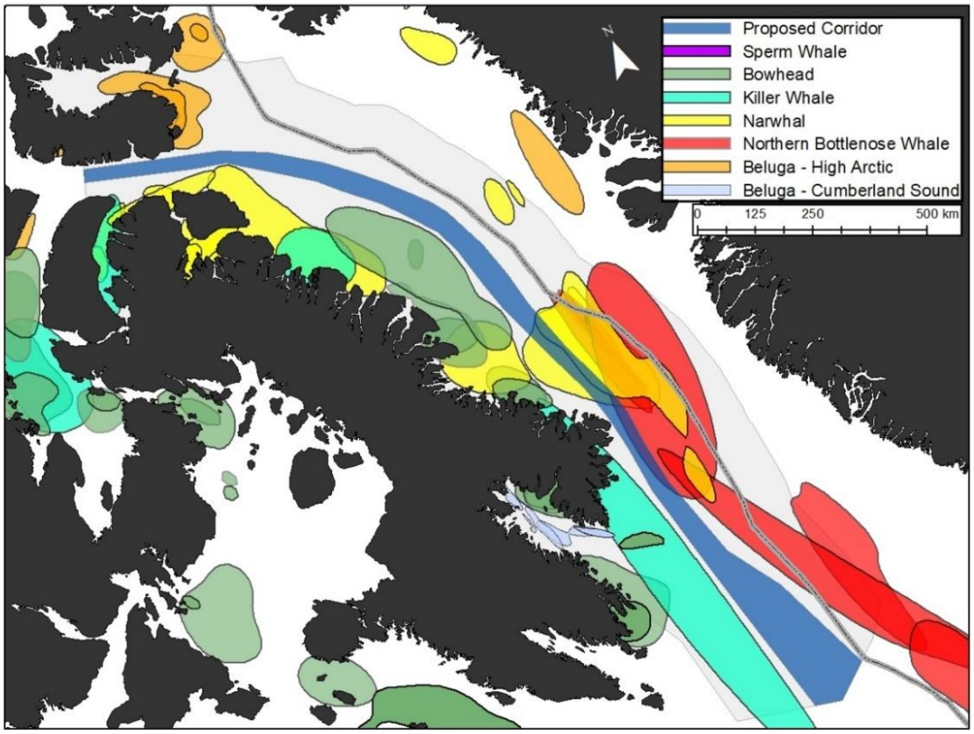
3.5. Developing the low-impact shipping corridor

3.5.1. Low-impact shipping corridor placement

The low-impact shipping corridor was developed using marine mammal distributions as the obstacles to navigate around. Developing the corridor to avoid the summed hotspot rasters would only serve to prevent sending vessel traffic through known overlap hotspots; the corridor would fail to account for areas that do not currently experience vessel traffic. The 50% utilization distributions for all species across all months were layered onto a single map. From this map, a primary corridor was placed that avoids as many high-use areas as possible while traveling through Davis Strait and Baffin Bay into Lancaster Sound. The map depicting the proposed low-impact corridor with the marine mammal 50% utilization distributions can be found in Figure 8.

Figure 8

Proposed low-impact shipping corridor overlaid with the 50% utilization distributions for all species across all examined months.



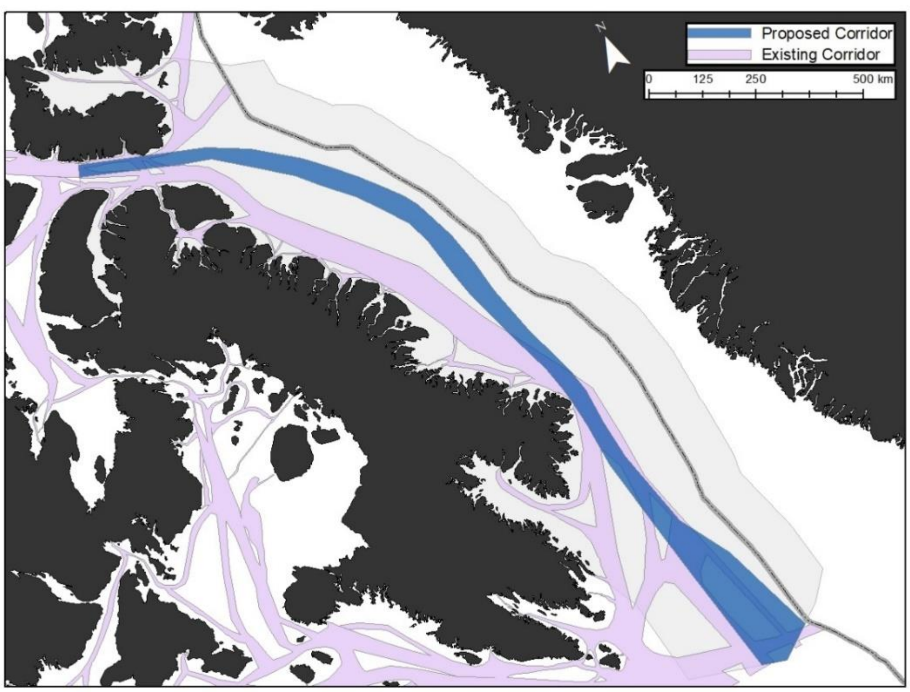
This corridor would provide access to secondary routes that connect to communities and other ports. This corridor, where possible, avoids areas of high marine mammal densities throughout the entire shipping season. From latitudes 69°11'N to 64°45'N the corridor was unable to be placed while completely avoiding marine mammal high-use areas. The November and December distributions of narwhal, as well as the September distribution of northern bottlenose whales, intersect with the proposed corridor.

3.5.2. Comparing the corridors

The corridors were compared by measuring the approximate distance to travel from the southern extent of the study area in Davis Strait to the northwestern extent in Lancaster Sound. The measured routes were not the shortest possible distance, rather they were an approximation of the path along the midpoints of the two corridors. The distance measured to travel through the study area via the existing NMTC was 2077 km. The distance measured to travel through the study area via the proposed shipping corridor was 2150 km. This represented an increased distance of 73 km, or 3.5%. The overlaid corridors are shown in Figure 9.

Figure 9

Map comparing the low-impact shipping corridor developed in this paper with the Northern Marine Transportation Corridor developed by Chénier et al. (2017).



4. Discussion

The findings of this study are in line with other current Arctic research that has found vessel traffic is increasing as the Arctic becomes more developed and so is the potential impact on Arctic marine mammals (Dawson et al., 2018; Halliday et al., 2022). The aim of the study was to assess the spatial distribution and intensity of the potential exposure through an analysis of the overlap between vessel traffic and marine mammal populations throughout the year. This analysis allowed for the design of a primary shipping corridor that avoided current overlap hotspots as well as areas that exhibit higher densities of marine mammals. This corridor avoids these sensitive areas throughout the year, based on the data available in this study, with a few unavoidable exceptions.

The produced shipping corridor represents a simple option for low-impact vessel navigation through the waters of the Canadian Arctic. The corridor is wide, relatively straight, and can remain in the same position throughout the ice-free season. Initially, the possibility of developing multiple corridors or a dynamic corridor that shifted throughout the year to account for cetacean movement was considered. Through the analysis conducted in this thesis however, it was found that a single corridor was a viable management strategy when paired with a slowdown area where needed. The fact that this corridor can have a fixed position throughout the shipping allows for easier implementation and enforcement.

The corridor only represents a primary shipping route; thus, the corridor is spatially simple. Upon the addition of secondary and tertiary corridors into narrower waterways, the corridor will increase in complexity; however, the fact that the primary route avoids sharp turns and narrow bottlenecks allows for easier navigation. The results of this study represent a straightforward and easy-to-implement stepping stone for further development of a more complex and sustainable shipping corridor.

Several areas were identified that are used by multiple cetacean species that exhibited high levels of overlap with monthly vessel traffic. The shipping corridor proposed in this paper aims to avoid these areas where possible, while the existing NMTC proposal does not account for these important areas. The waters immediately surrounding Bylot Island Bird Sanctuary in Eclipse Sound demonstrated high levels of overlap for narwhal, killer whales, and bowhead whales. This protected area houses valuable habitat for migratory bird species, and the waters surrounding it has high densities of narwhal and killer whales. Due to the narrowness of Eclipse Sound, the waters adjacent to the Bylot Island Bird Sanctuary cannot be avoided by shipping routes, and therefore alternate mitigation measures, like vessel slowdowns, should be implemented. Current vessel traffic that is travelling through Eclipse Sound to the Mary River Iron Mine follows a company-enforced vessel slowdown protocol according to their annual report (Baffinland Iron Mines Corporation, 2024).

Another area of ecological value for the examined marine mammals is the shallow waters lining the coast of Baffin Island from Qikiqtarjuaq to Eclipse Sound, including the Ninginganiq National Wildlife Area (NWA), specifically for the bowhead whales. It should be noted that the Ninginganiq NWA was established specifically to protect nearshore bowhead habitat (Government of Canada, 2024); however, high levels of overlap were still noted in this study, particularly in the offshore areas outside of Ninginganiq NWA. These shallower waters (compared to the deeper centre of Baffin Bay) act as feeding grounds for bowhead whales in Baffin Bay (Government of Canada, 2024), and the current levels of overlap are extremely high. The corridor proposed in this thesis avoids this important area, however secondary corridors extending towards the communities on Baffin Island, such as Clyde River and Qikiqtarjuaq, will have to consider alternate mitigation measures. The NMTC notably runs directly through this area and could result in further impact on vulnerable bowhead populations. Finally, an area that has high levels of overlap for multiple species is the Disko Fan Conservation Area. This is an area protected by the Federal government to reduce impacts on overwintering habitat and food source for narwhal, as well as to conserve native coral populations. Although acting as a conservation area for narwhal, the only restricted activities in the area involve bottom-contact fishing, with no consideration given to vessel traffic impacts. Both the corridor developed in this paper and the NMTC proposal avoid this area; however, current overlap remains high.

When comparing the corridor developed in this paper to the NMTC proposed by Chénier et al. (2017), the difference between the two corridors was examined in terms of distance travelled through the study area, as well as the potential for a reduction in vessel-marine mammal overlap. Comparing the difference in travel distance between corridors allowed us to assess one aspect of the economic impact of implementing the newly developed shipping corridor. An increased travel distance, like the increase from implementing the proposed corridor, means that industries making use of the Northwest Passage would experience higher shipping transit time that could reduce profitability of their business (Khon et al., 2010). The increase demonstrated in this paper between the NMTC proposal and the corridor proposed here was 3.5%, an increase that, while small, must be considered when discussing the implementation of the low-impact shipping corridor. Moreover, a point not considered in this paper was that the proposed corridor is further offshore, which increases the distance travelled for vessels taking secondary corridors to communities.

While the NMTC may confer economic and convenience advantages, there is a considerable environmental benefit to implementing the low-impact corridor through the reduction in potential overlap between vessel traffic and cetacean populations. As demonstrated by the low increase in travel distance between the corridors, they are fairly similar in their placement in certain locations. The key spatial differences, however, lie along the Eastern coast of Baffin Island, north of Qikiqtarjuaq, and in Lancaster Sound. The shallow waters off the coast of Baffin Island from Qikiqtarjuaq to Eclipse Sound provide valuable habitat for bowhead whales, narwhal, and killer whales. The high population densities of these whales in this area have resulted in considerable overlap with vessel traffic, and the corridor proposed by Chénier et al. (2017) runs straight through this habitat. This area is avoided by the low-impact corridor developed in this paper.

The other notable difference between the NMTC and the corridor defined in this work involves the navigation of Lancaster Sound. While the NMTC travels freely throughout the Sound, the proposed corridor restricts travel to the northern half of the waterway. This corridor defined by this research was designed in this way due to the analysis in this thesis identifying the southern waters of Lancaster Sound as a high-density area for narwhal populations.

While the primary objective of the corridor developed in this thesis was to avoid areas with higher marine mammal usage, there were certain examples where avoidance was not a viable impact mitigation measure. This is depicted in Figure 9, where there are utilization distributions overlapping with the proposed corridor. Specifically, the November and December distributions of narwhal and the September distribution of northern bottlenose whales intersect with the proposed corridor from latitudes 69^{o}11’N to 64^{o}45’N. This overlap is a result of the narrowing of the area between Baffin Island and the Canada-Greenland maritime border at Cape Dyer. As avoidance in this area is not possible in those months, alternate mitigation measures such as vessel speed restrictions should be considered.

This study was conducted as a master’s thesis; thus, the scope of the research had to remain limited due to time and cost. Such limitations include that the list of species studied in this paper does not include all marine species, and focuses specifically on cetacean species with available satellite telemetry data. There are other marine mammals that reside in the study area, such as pinnipeds, marine bird species, fish species, and more, that were not considered when assessing overlap with vessel traffic due to a lack of data. Furthermore, for the six species that were studied, datasets are limited, and more data is costly and difficult to collect. This paper relied on marine mammal data from a period of more than 30 years, and still the number of recorded individuals remains low. Another limitation is that this study estimates potential exposure to vessel traffic, but cannot address the impacts of that exposure. Species that are more exposed to human activity through their migratory corridors may have less negative effects from intersecting with vessel traffic when compared to the more reclusive species (Halliday et al., 2020). Some species, such as narwhal and beluga, have been shown to be sensitive to vessel exposure (Finley et al. 1990), whereas other species, like sperm and northern bottlenose whales, may be exposed to more vessel traffic year-round, and may be less impacted by vessels. Other limitations relate to the scope of this research project in terms of how the shipping corridor was designed. As discussed earlier in this paper, this corridor proposal only represents an environmental perspective in developing a sustainable shipping corridor, but economic and social aspects must also be considered.

There is no doubt that the limitations discussed above influenced the results and interpretations of data throughout this study. Additional issues include how the low and varied number of individuals for different marine mammal species may have led to a lack of representativeness in the analytical process. In a mammal dataset with a low number of individuals, such as narwhal, each individual whale had more quantitative influence on the overlap analysis than in a species with a larger dataset, such as bowhead whales. Additionally, the placement of the corridor itself only avoids high density spots for the examined marine mammal species. Without further analysis with a more comprehensive dataset, there exists the chance that the corridor proposed in this paper could travel through high-use areas for other wildlife. The proposed corridor is also weighted evenly between species inputs. This means that the corridor fails to account for species that are less exposed, and therefore, potentially less resilient to human interactions, like narwhal. The analysis assigns them the same level of negative anthropogenic impact from vessel interaction as it does killer whales, a species far more exposed to human activity. Finally, the placement of this corridor is informed by only ecological data. The proposed corridor suggests an increase in vessel travel distance, negatively impacting the cost for industries to develop and use the Northwest Passage. From a social perspective, this corridor also does not consider Inuit use in its placement. Subsistence hunting and community resupply are two important use cases for the communities in the study area and should be considered in further development of a shipping corridor (Dawson et al., 2018).

The main avenues of future research should fall under the three pillars of sustainable development: environmental, economic, and social. Potential environmental research topics that could produce a higher quality shipping corridor are further surveying to produce more representative species datasets, as well as better understanding of how human activity realistically impacts the present species. The economics of developing the Canadian Arctic should also be investigated to help develop a shipping corridor, since the Northwest Passage can act as a shorter passage for global shipping, and the mostly undeveloped landscape and waters represent great economic potential. Social research, such as the research being conducted through the Arctic Corridor Research Project led by Dr. Jackie Dawson (Dawson et al., 2020) should continue to develop as well. The ability to receive and use input in the development of a shipping corridor from local communities will prove invaluable in the long-term success and adoption of such a corridor.

5. Conclusion

In today's warming Arctic, the lengthening ice-free season and subsequent increase in vessel traffic requires action. The impact that these vessels pose to native marine wildlife necessitates the implementation of conservation methods in order to develop the Arctic in a sustainable way. In this thesis, I have proposed the implementation of a sustainable shipping corridor through the Canadian waters of Baffin Bay and Davis Strait and have developed a preliminary shipping corridor that aims to reduce the overlap between vessels and marine mammals. After assessing the current trends in vessel-marine mammal overlap, I developed a low-impact shipping corridor by assessing the spatial distribution of marine mammals throughout the shipping season and identifying a route that would avoid high density marine mammal areas. The proposed corridor successfully avoids these areas for most of the shipping season; however, in the few instances where avoidance was impossible, the alternative mitigation measure of vessel speed restrictions was suggested instead. The proposed corridor is compared to a corridor developed by Chénier et al. (2017) to determine how reducing impacts on marine mammals would differ from a corridor developed through focusing on navigability. Developing a corridor that aims to reduce the anthropogenic impacts of increasing vessel traffic on marine mammals is a vital step towards a sustainable future for the Canadian Arctic.

The results of this paper outline how overlap between marine mammals and vessel traffic has increased in recent years, as well as offering a method of mitigating the negative impacts of this increasing overlap. To offer a truly sustainable shipping corridor however, we recognize that a holistic solution involving consultation with all users of the Canadian Arctic must be pursued, balancing environmental, economic, and social benefits. While the scope of the research conducted in this paper is limited, the results provide a simple and optimistic option on which to base further discourse and decisions. It is hoped that this paper spurs discussion and contributes meaningfully towards the community of Arctic research and conservation, while also providing a stepping stone for future development of a sustainable shipping corridor. Further and continued research into the sustainable development of the Canadian Arctic is of the utmost importance, as the Arctic represents one of the few remaining undeveloped environments in the world, and responsible and proactive policies are needed that support the preservation of this unique ecosystem.

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Appendix: Additional Result Maps

Figure A-1

Bowhead-vessel traffic overlap for September and October of 2016 and 2019.

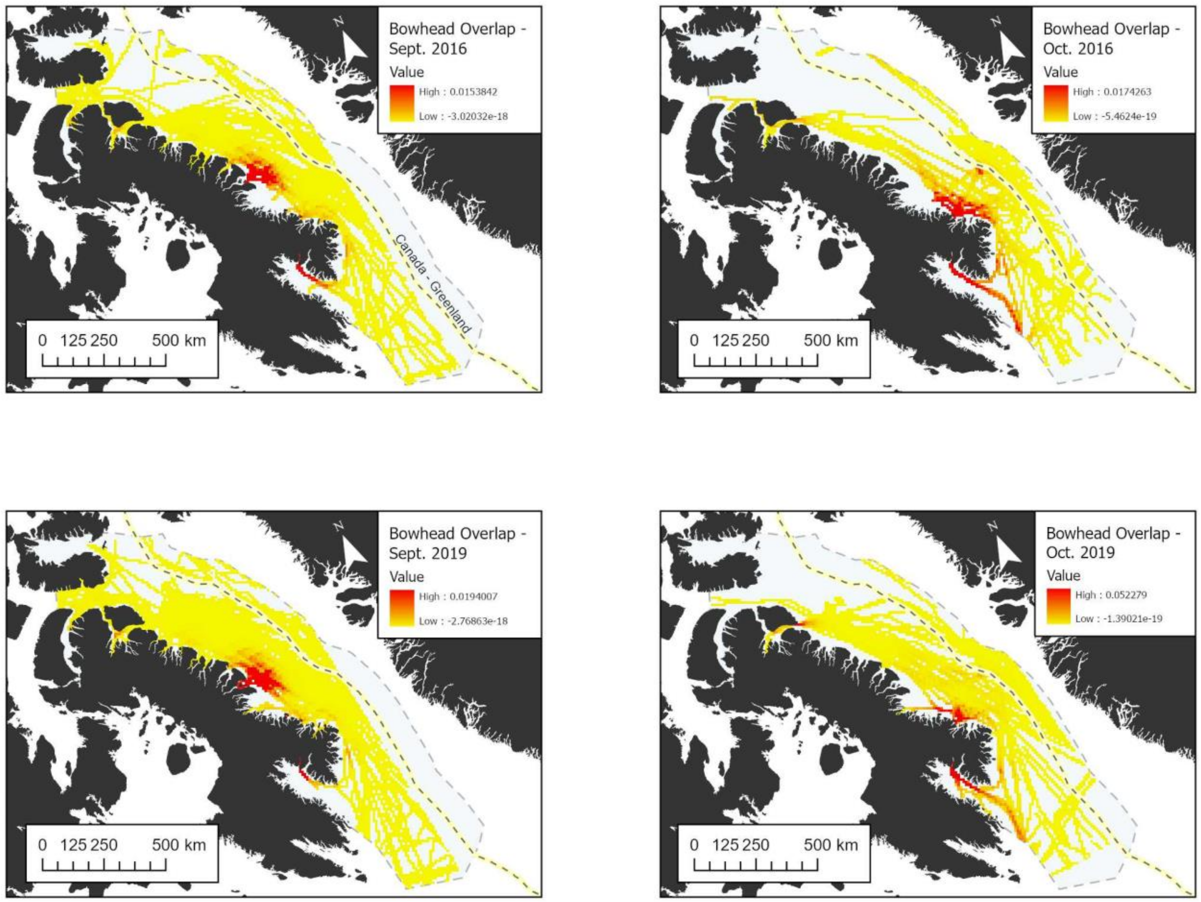

Figure A-2

Cumberland Sound beluga-vessel traffic overlap for September and October of 2016 and 2019.

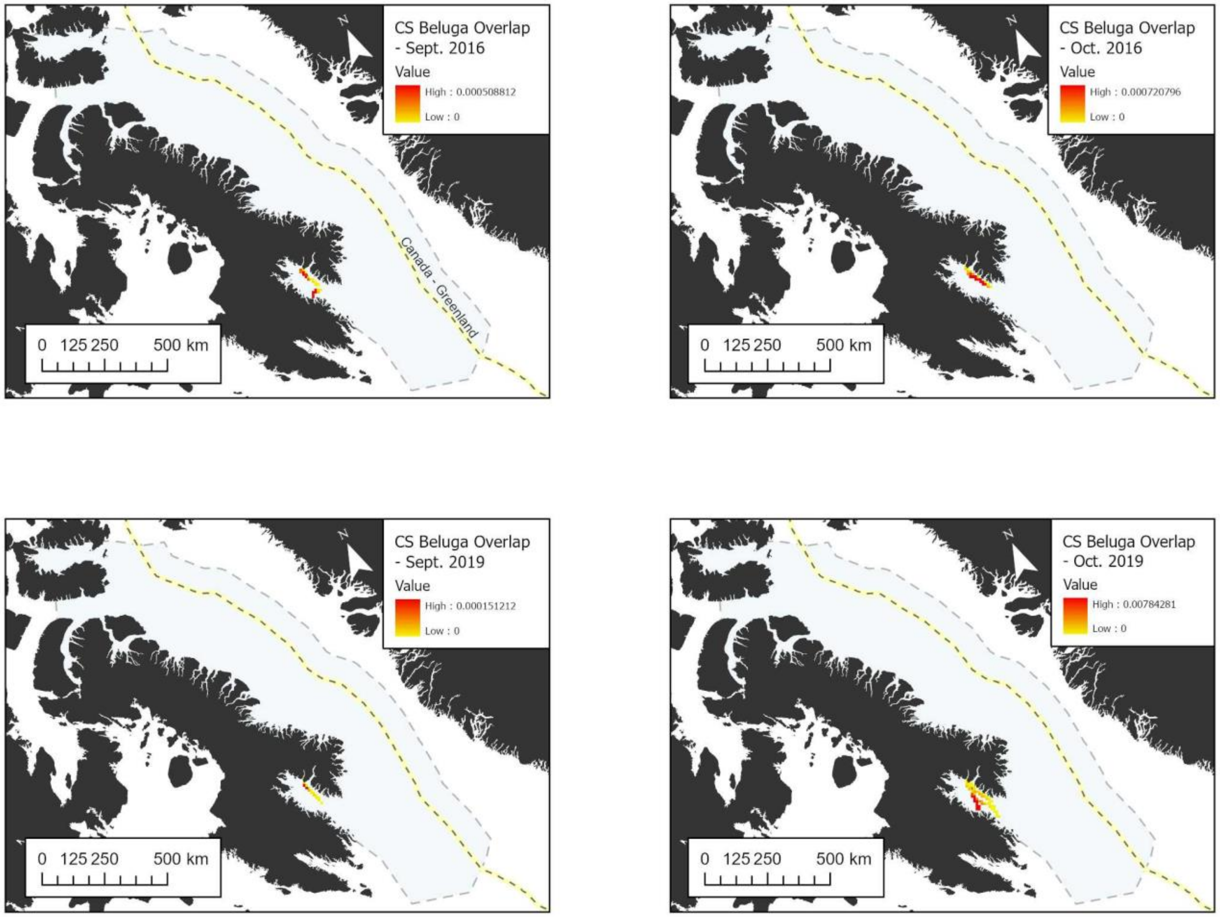

Figure A-3

High Arctic beluga-vessel traffic overlap for September and October of 2016 and 2019.

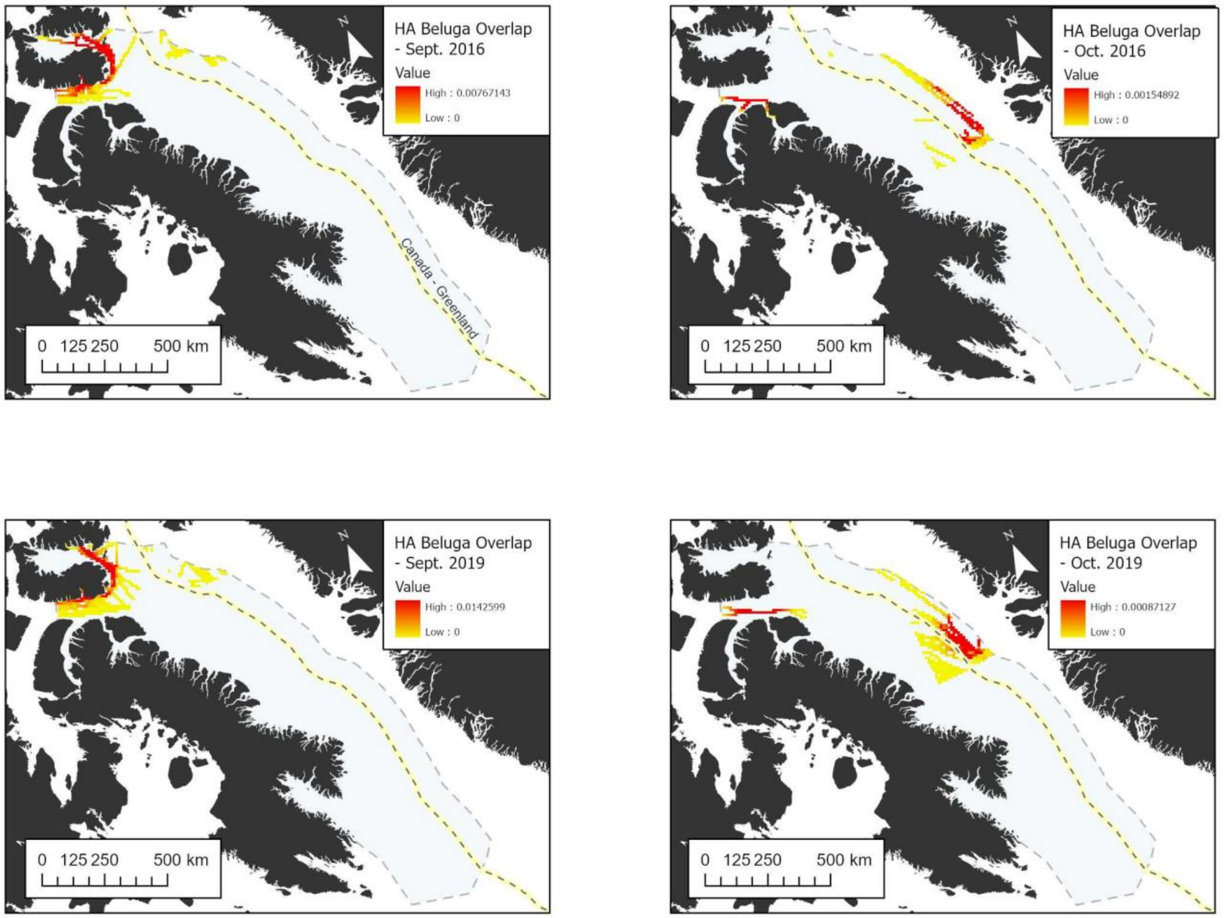

Figure A-4

Killer whale-vessel traffic overlap for September and October of 2016 and 2019.

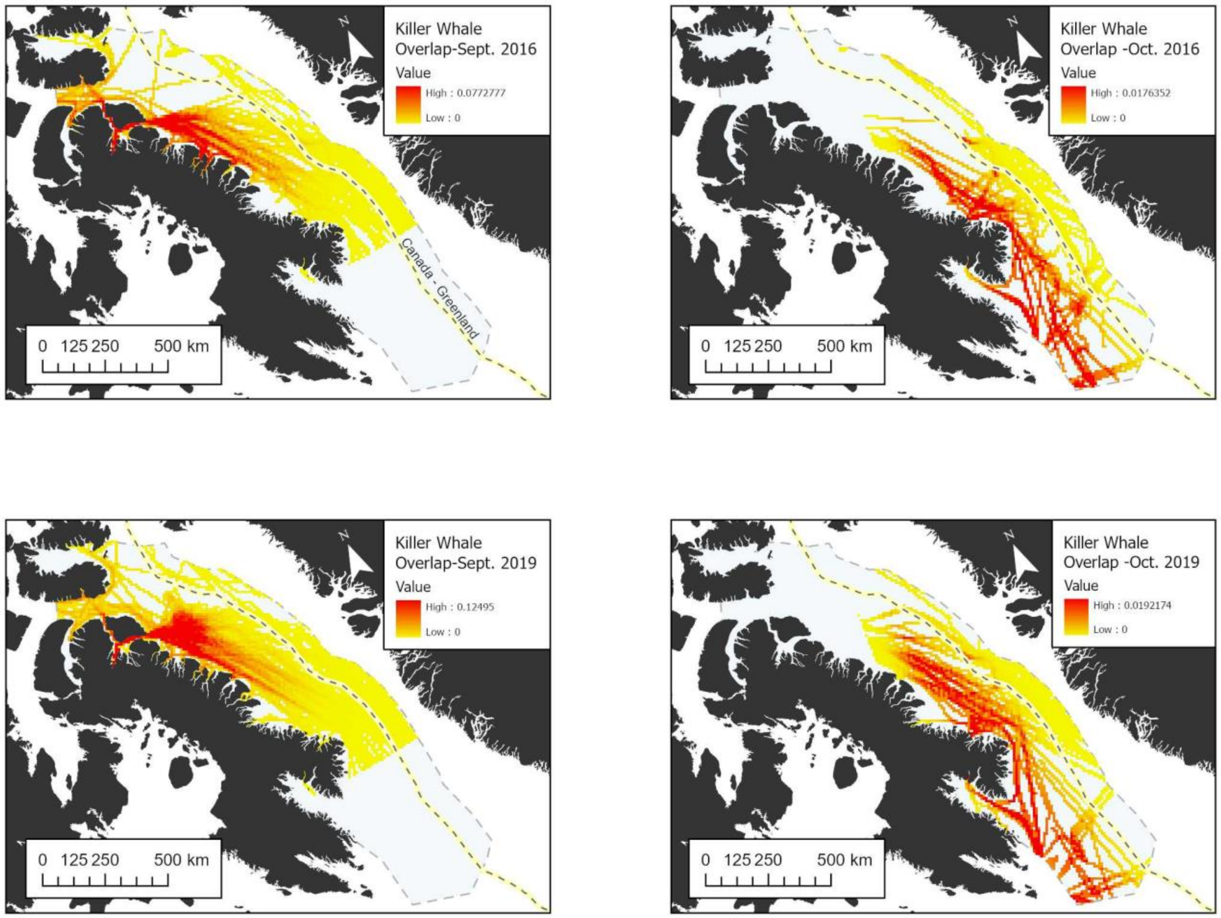

Figure A-5

Narwhal-vessel traffic overlap for September and October of 2016 and 2019.

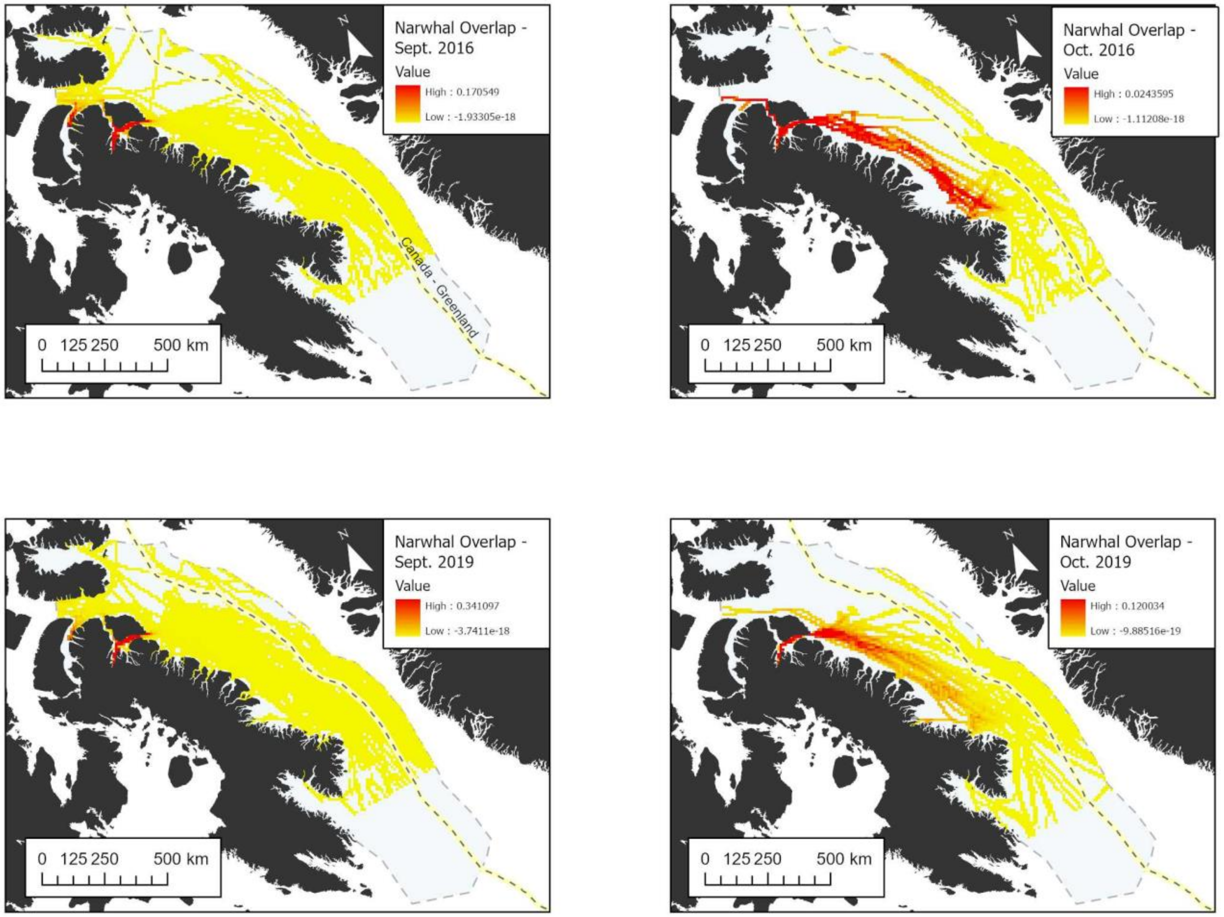

Figure A-6

Northern bottlenose whale-vessel traffic overlap for September and October of 2016 and 2019.

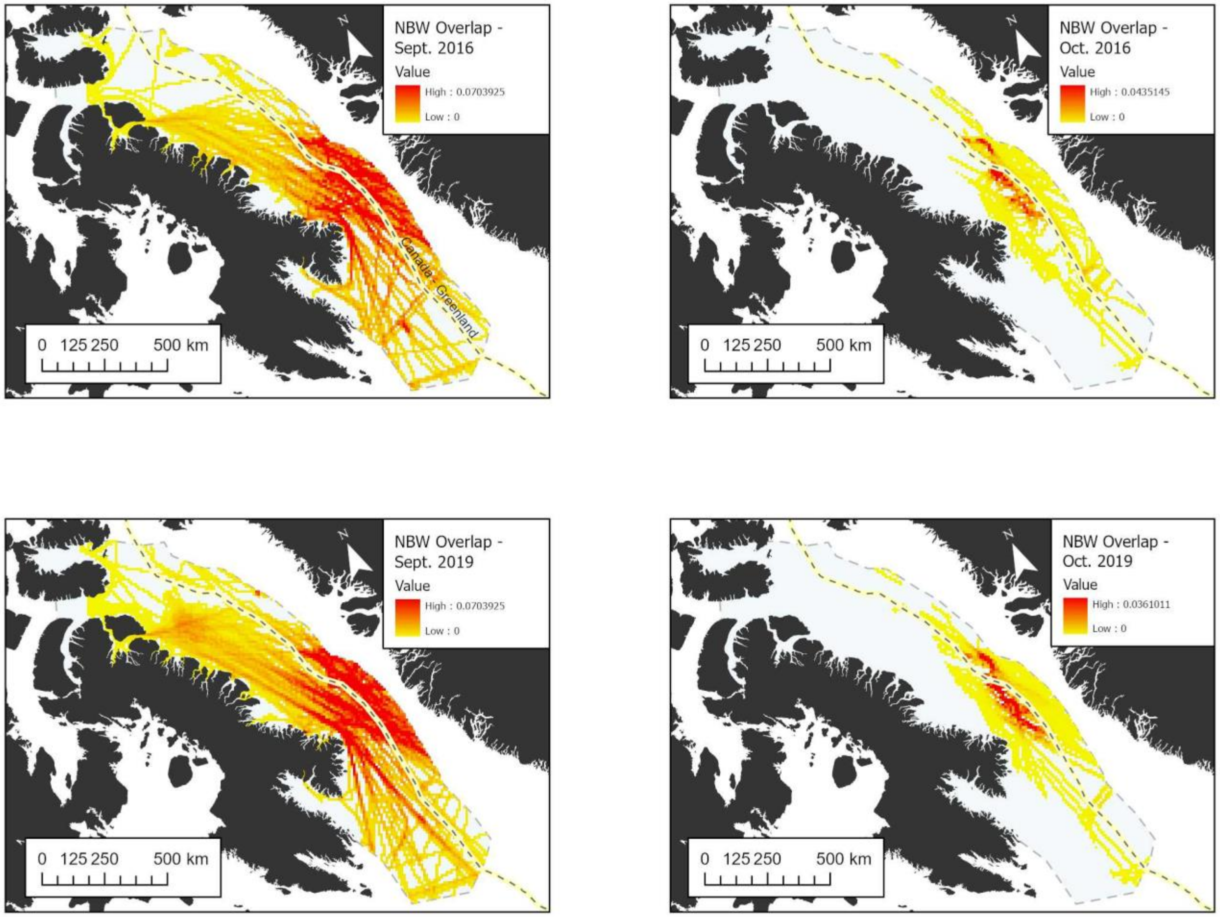

Figure A-7

Sperm whale-vessel traffic overlap for September and October of 2016 and 2019.

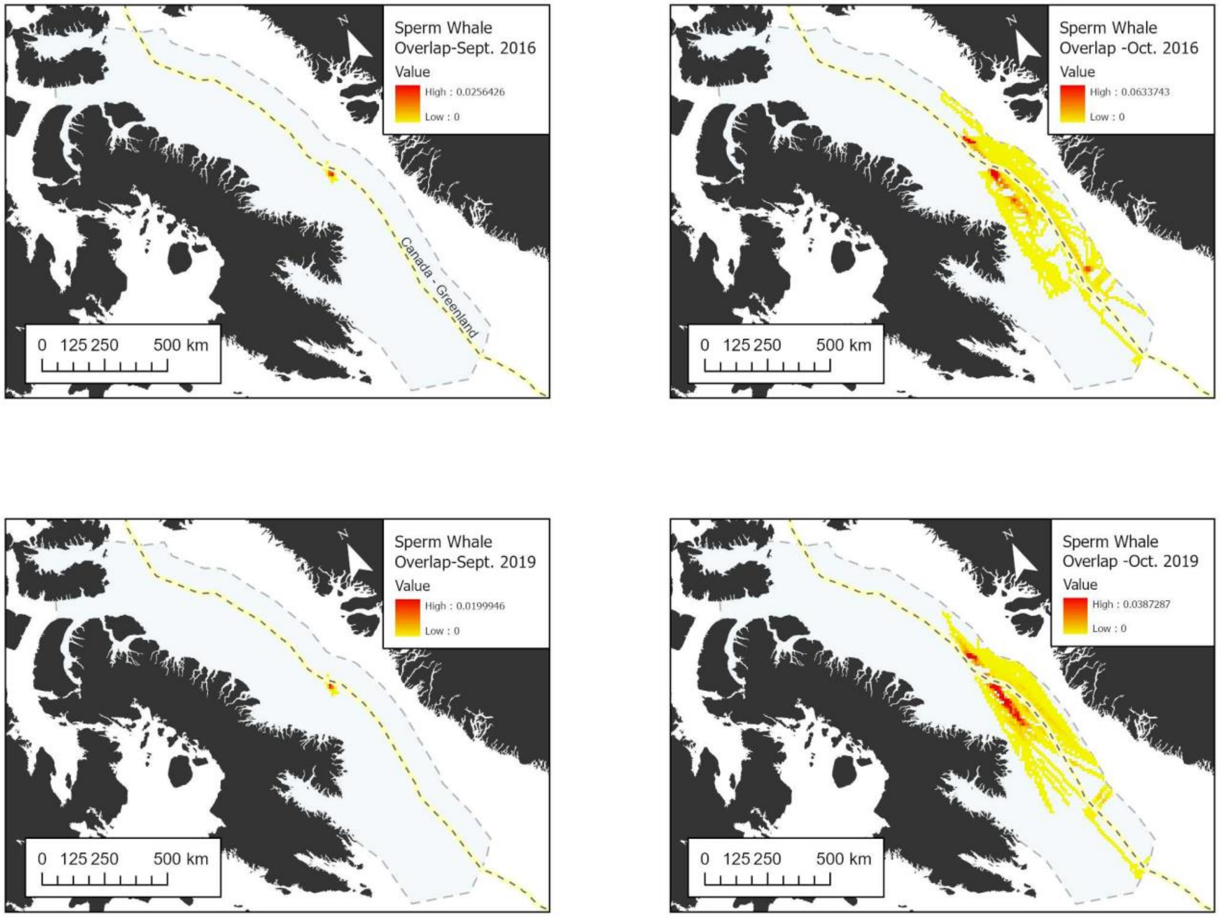

Figure A-8

Study area map of summed overlap hotspots for all species in July 2019.

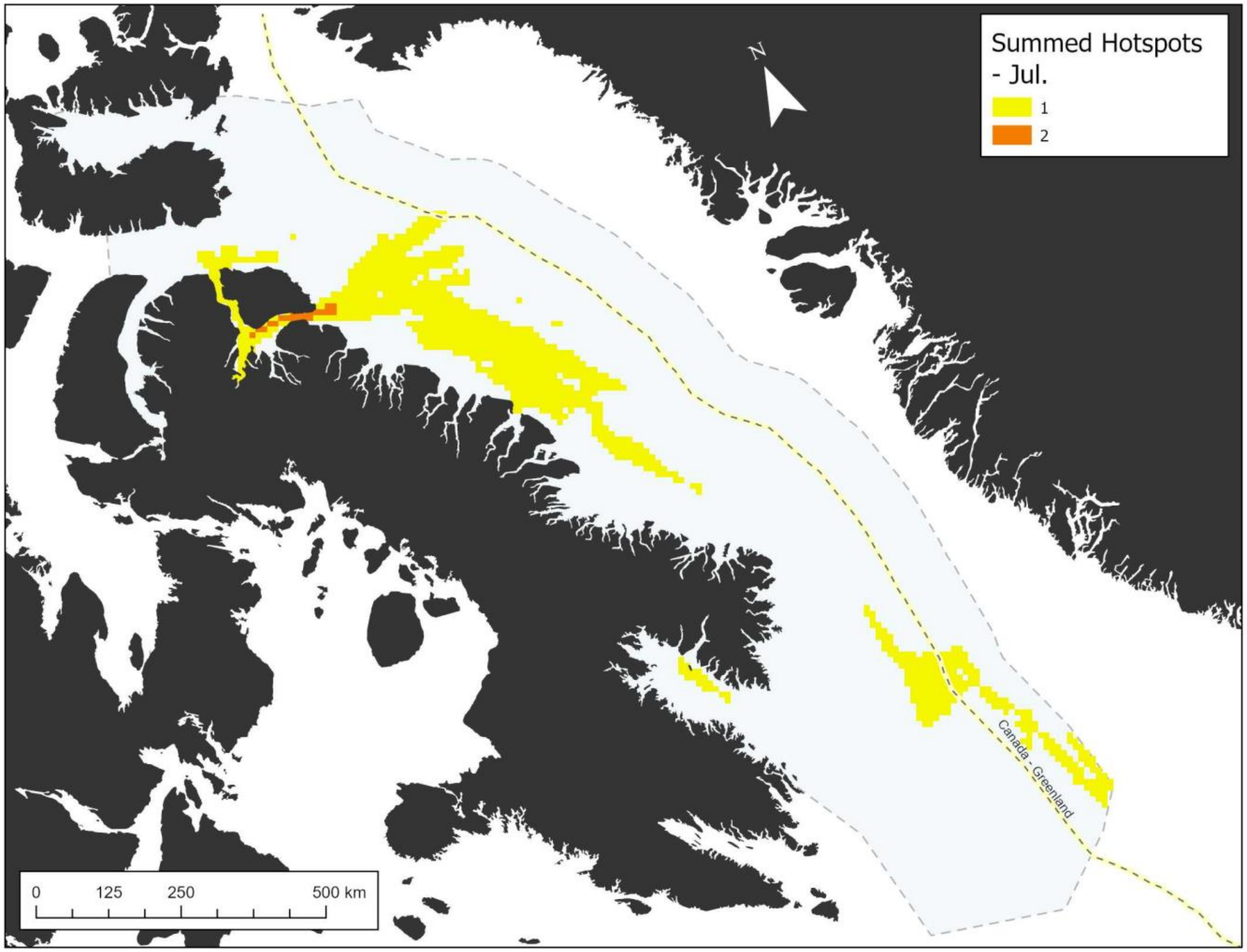

Figure A-9

Study area map of summed overlap hotspots for all species in August 2019.

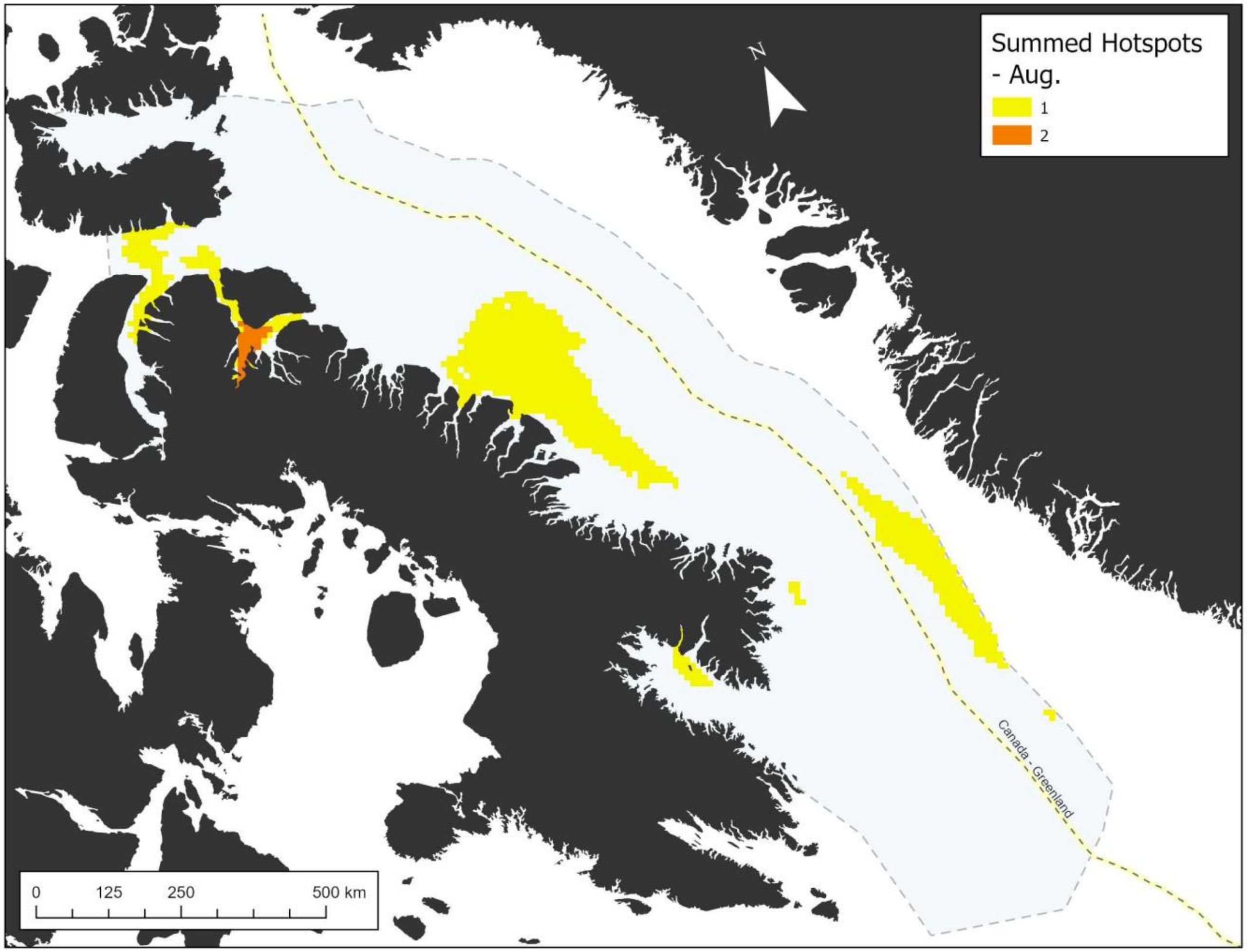

Figure A-10

Study area map of summed overlap hotspots for all species in September 2019.

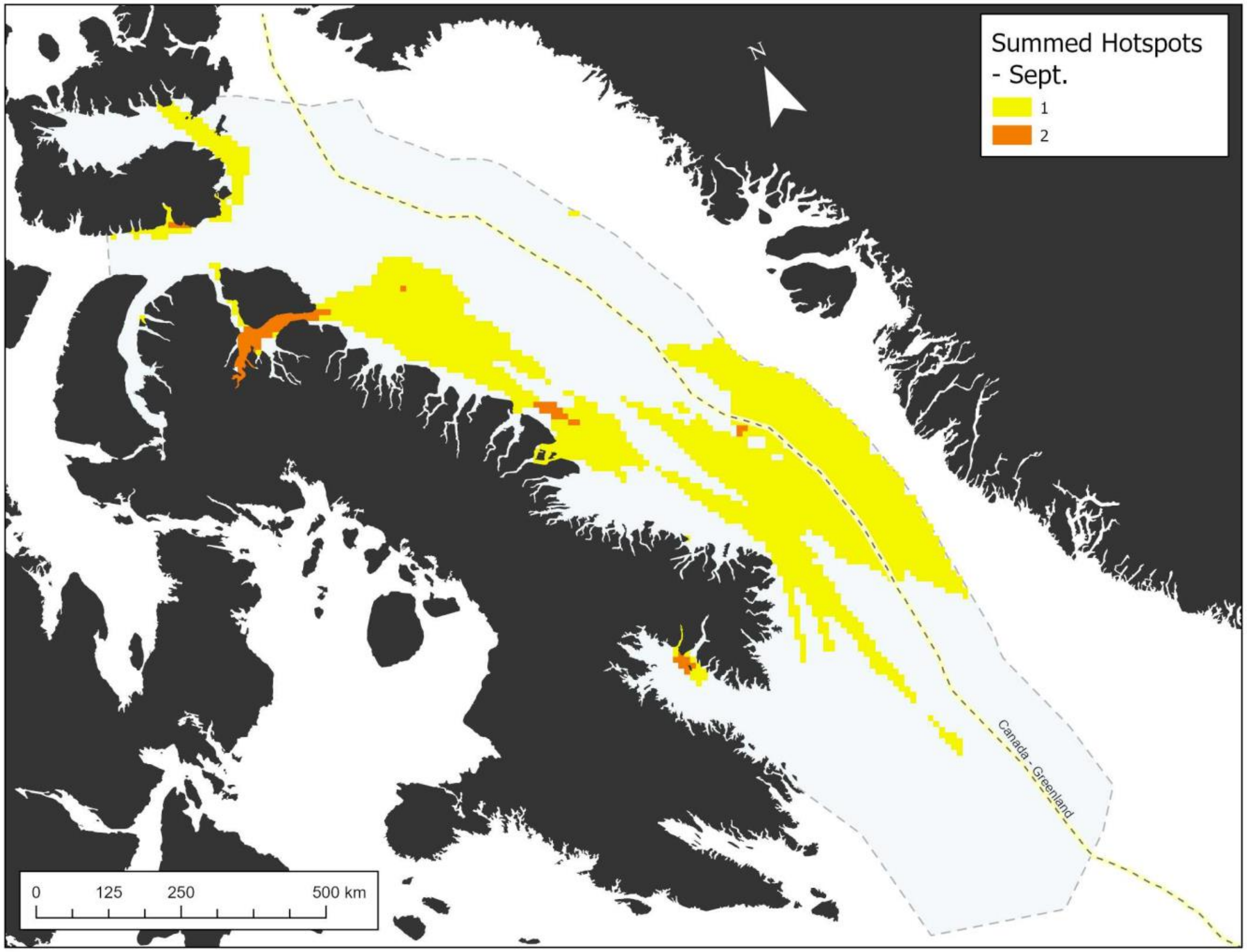

Figure A-11

Study area map of summed overlap hotspots for all species in October 2019.

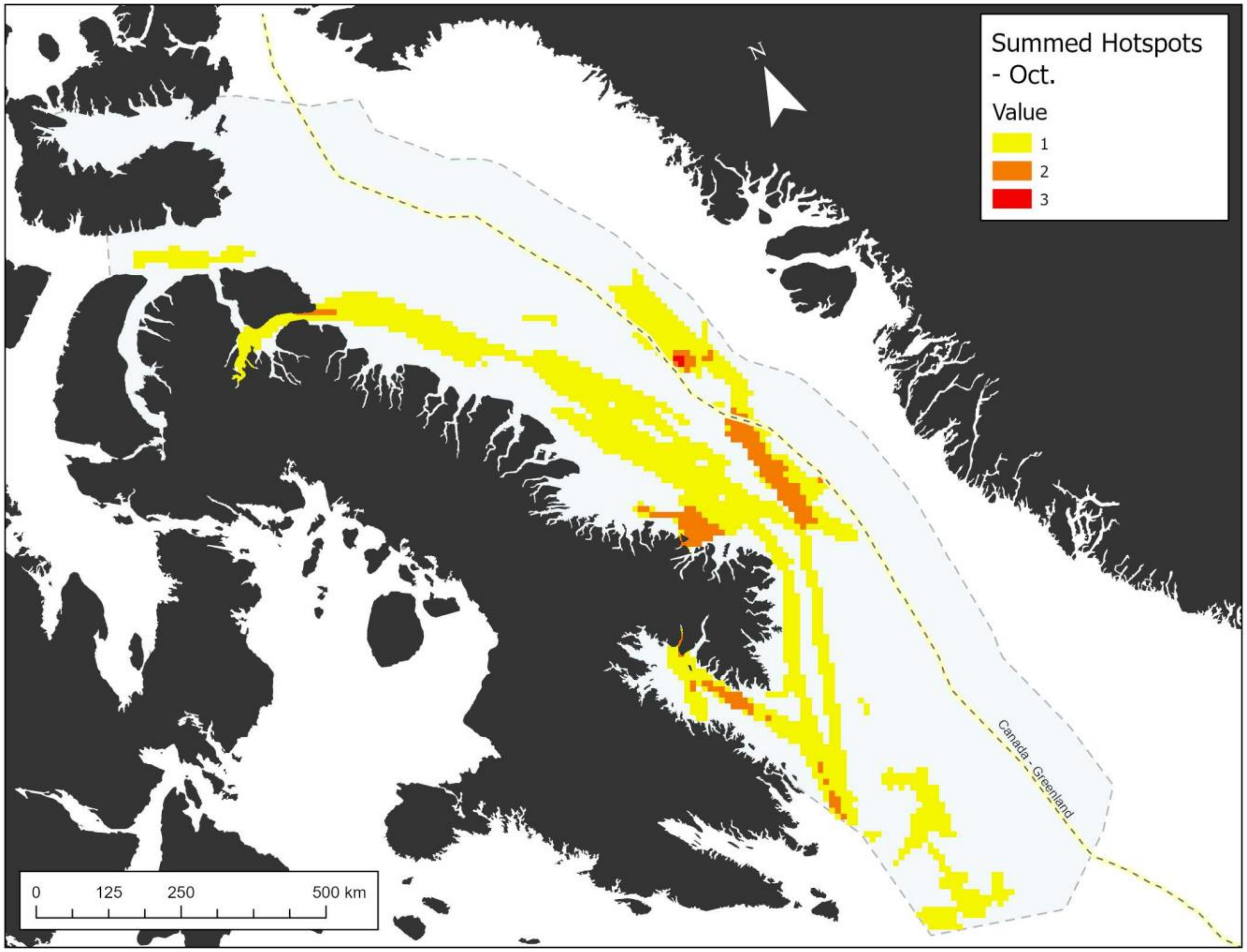

Figure A-12

Study area map of summed overlap hotspots for all species in November 2019.

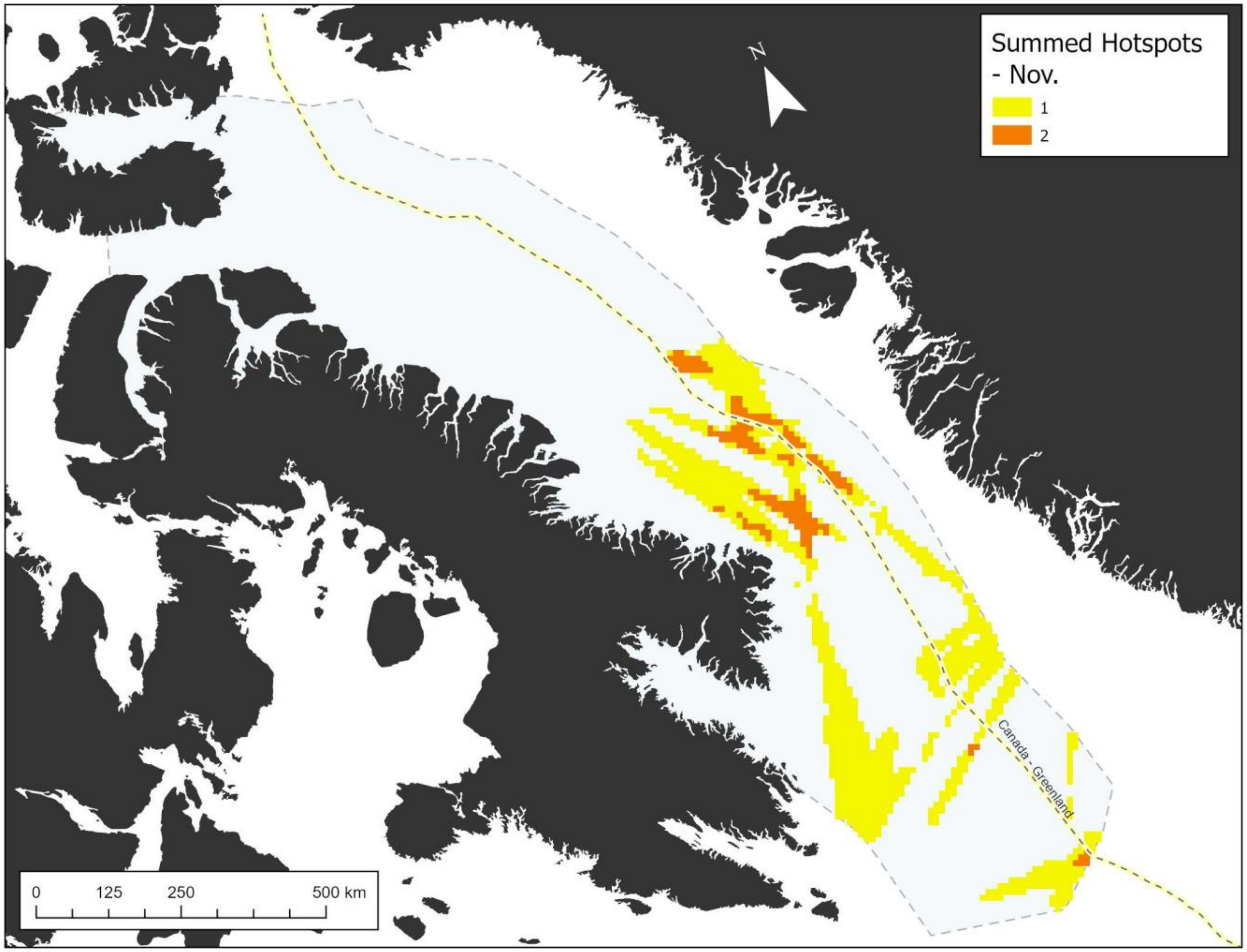

Figure A-13

Study area map of summed overlap hotspots for all species in December 2019.

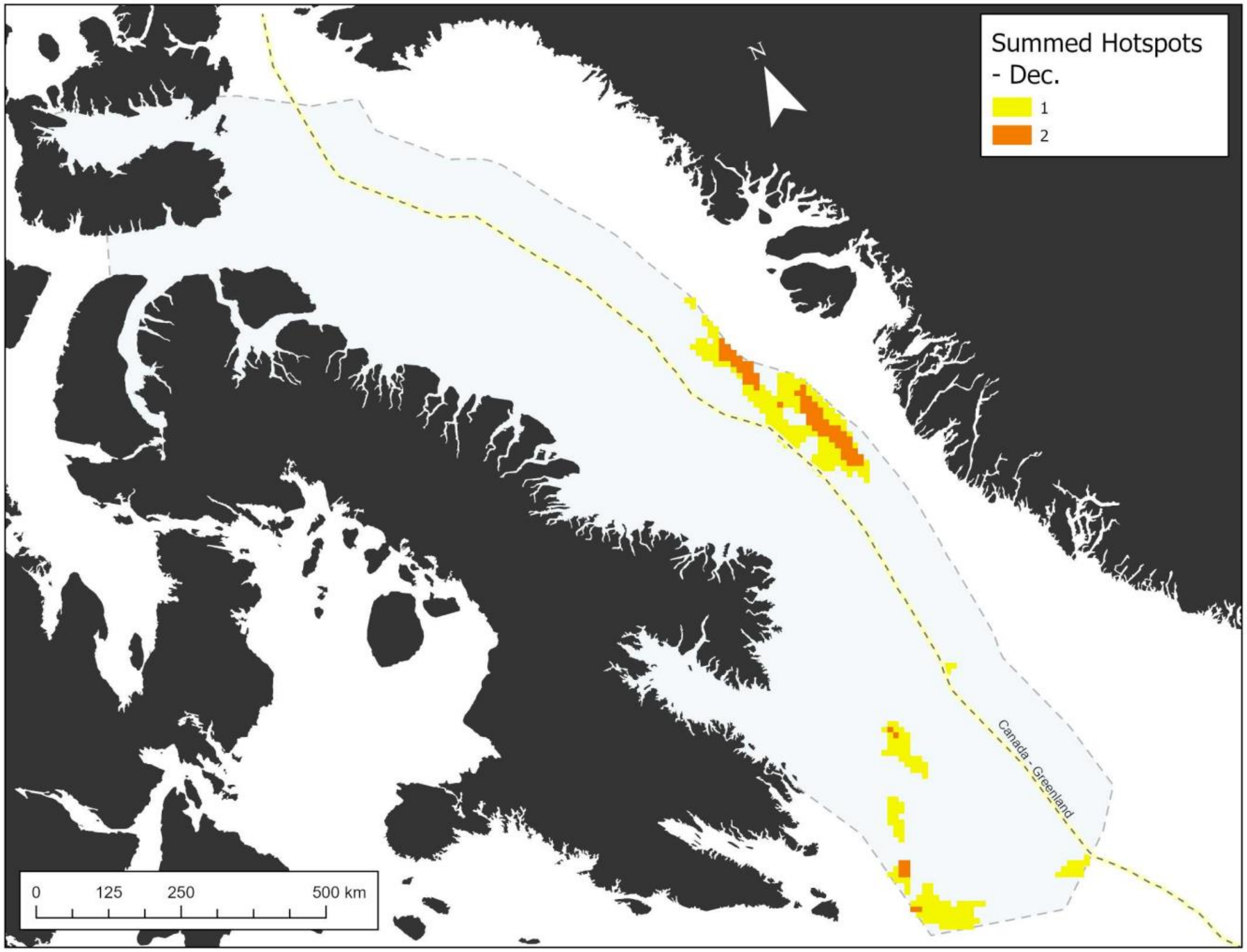

Figure A-14

Comparison of existing corridor with summed overlap hotspots for all species in July 2019.

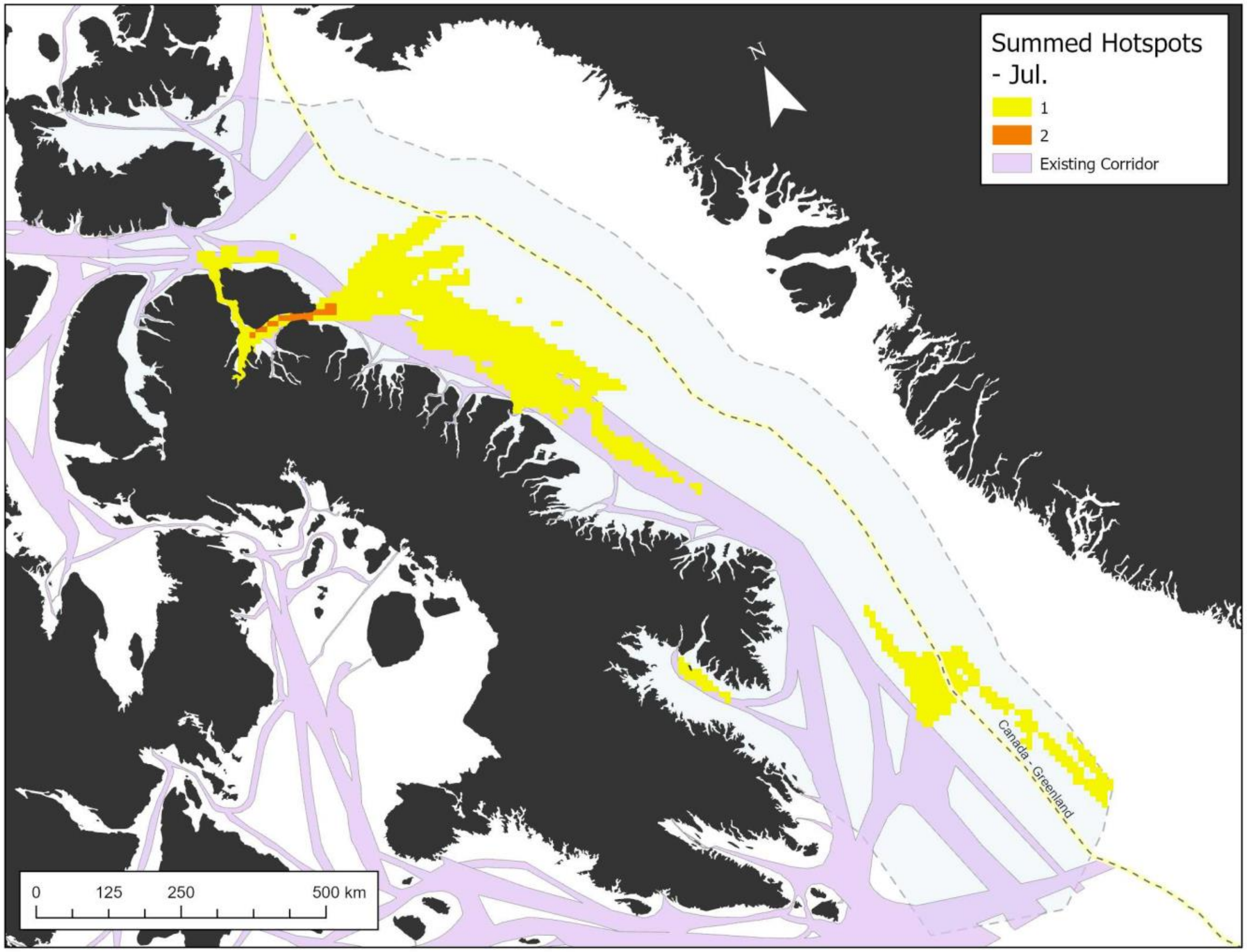

Figure A-15

Comparison of existing corridor with summed overlap hotspots for all species in August 2019.

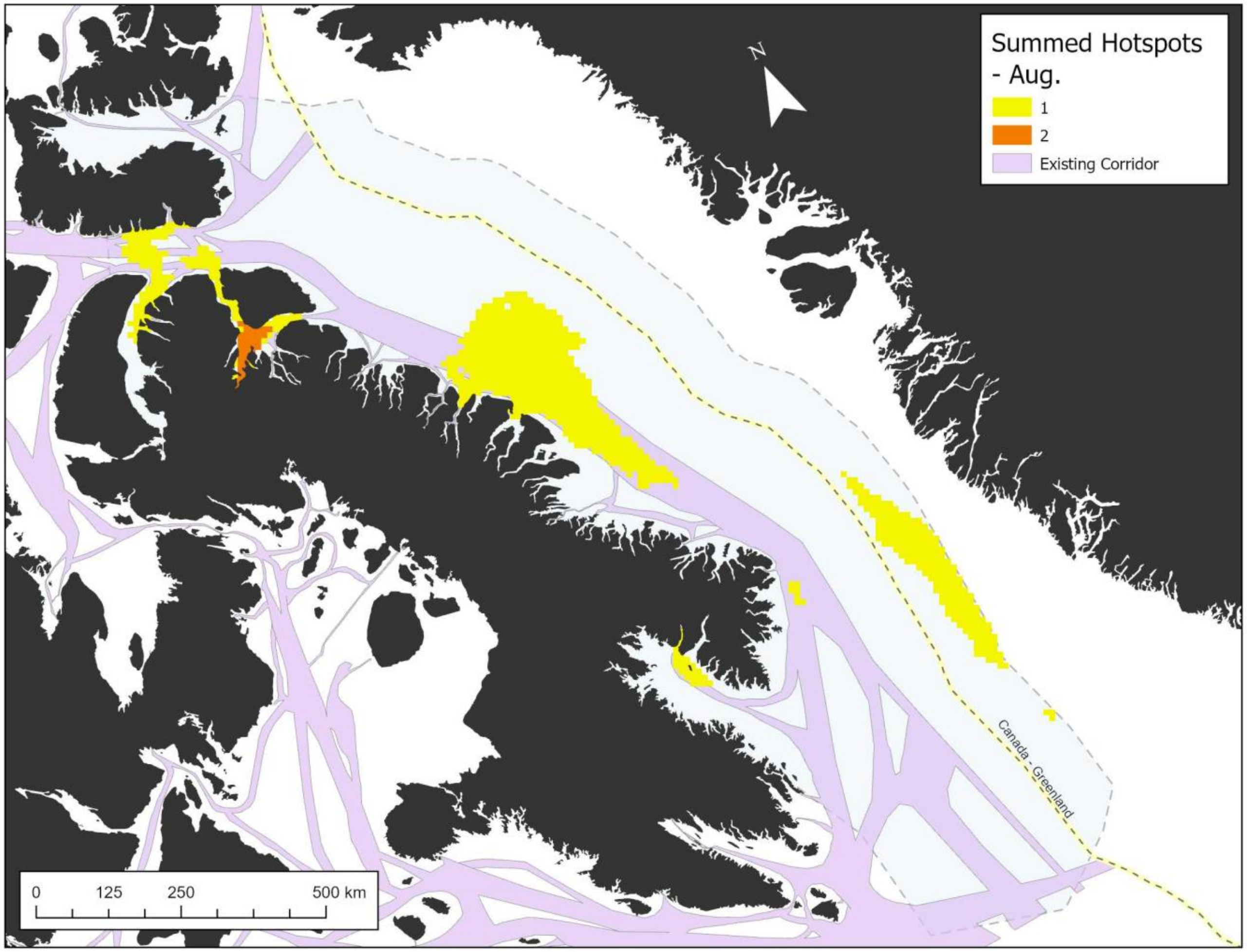

Figure A-16

Comparison of existing corridor with summed overlap hotspots for all species in September 2019.

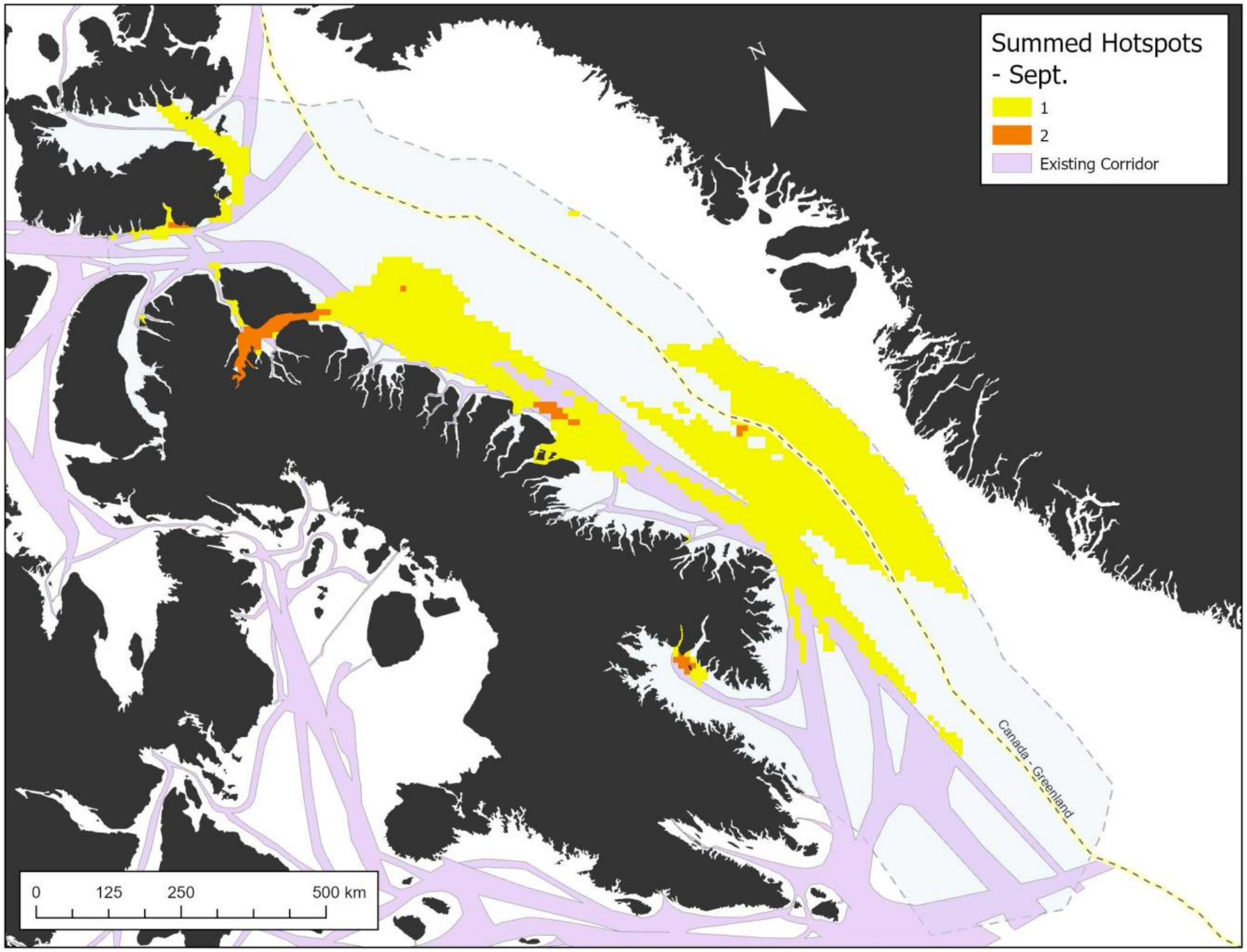

Figure A-17

Comparison of existing corridor with summed overlap hotspots for all species in October 2019.

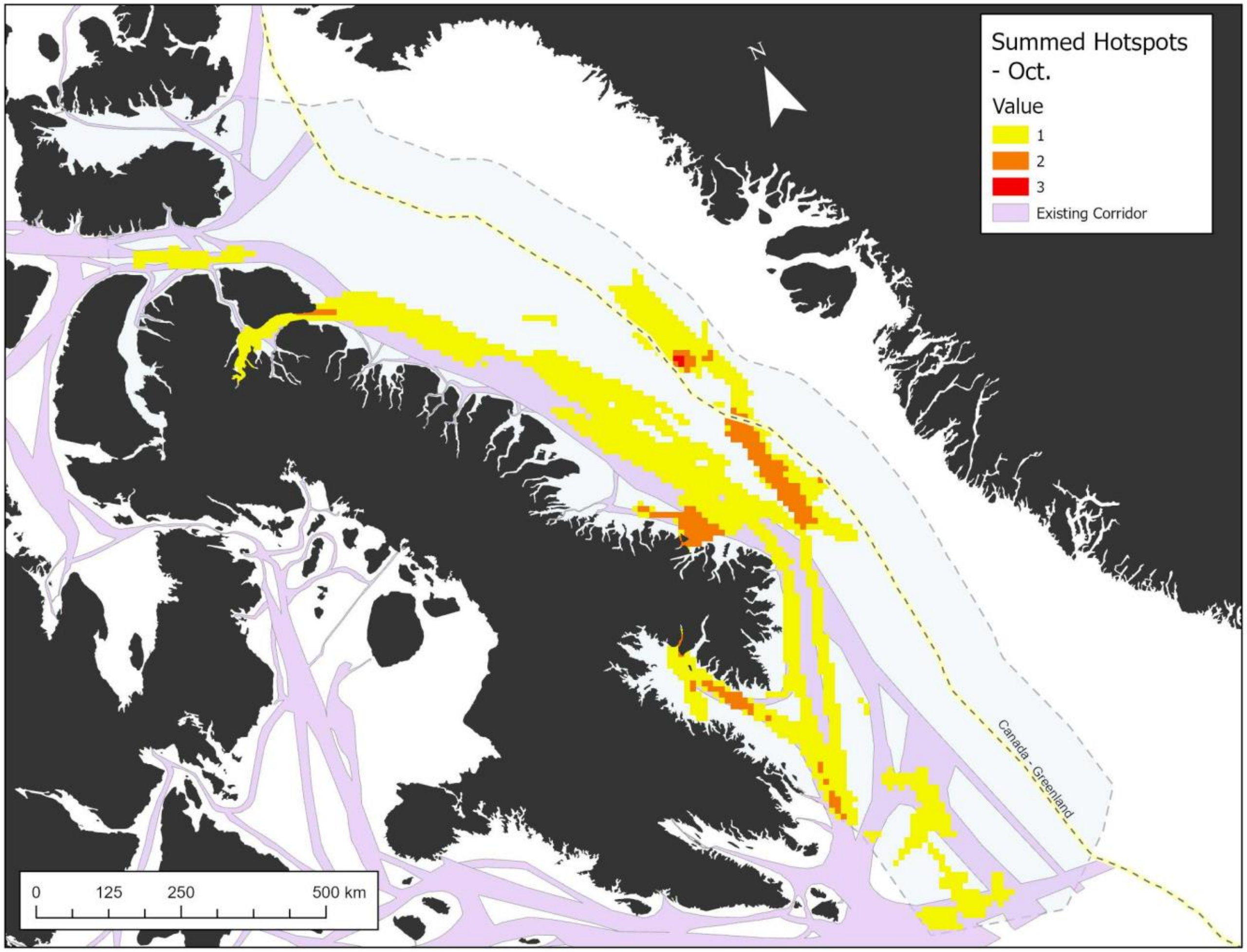

Figure A-18

Comparison of existing corridor with summed overlap hotspots for all species in November 2019.

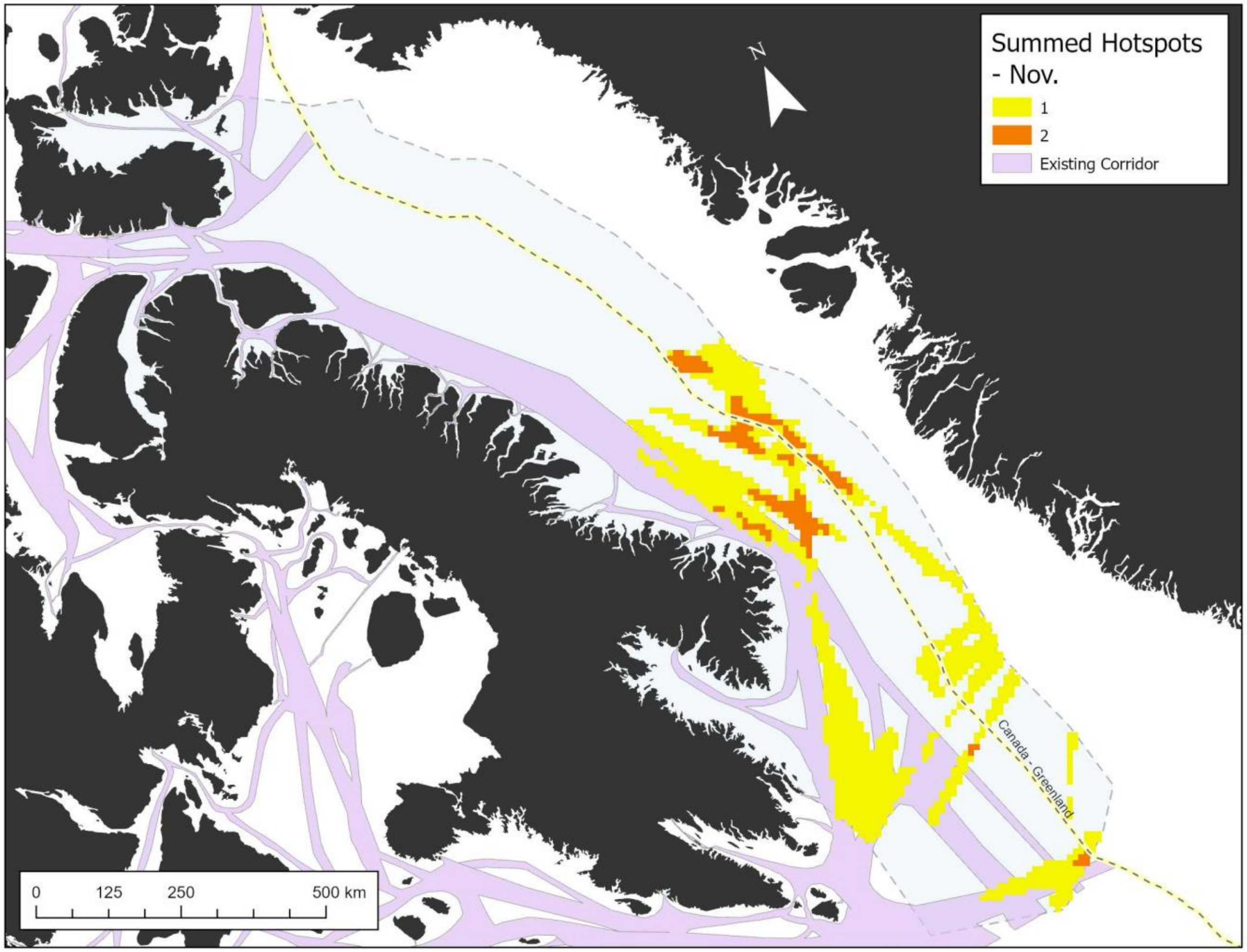

Figure A-19

Comparison of existing corridor with summed overlap hotspots for all species in December 2019.