Biological Conservation 276 (2022) 109820

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Overlap between bowhead whales (*Balaena mysticetus*) and vessel traffic in the North American Arctic and implications for conservation and management

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ARTICLE INFO

Keywords:
Automatic identification system
Bering-Chukchi-Beaufort
Cetacean
Conservation
Eastern Canada-West Greenland
Ship strikes
Vessel strikes

ABSTRACT

Collisions between vehicles and wildlife is a global conservation concern, and vessel strikes are a leading cause of serious injury and mortality for baleen whales. Yet vessel strikes have rarely been studied in the Arctic. Vessel traffic is increasing throughout the Arctic as sea ice is declining, leading to increased overlap between vessels and whales. We examined hypothetical vessel strike risk for the Bering-Chukchi-Beaufort (BCB) and Eastern Canada-West Greenland (ECWG) populations of bowhead whales during the open-water shipping season. We used satellite telemetry and aerial survey data to calculate monthly relative density of both populations, and satellite vessel tracking data to calculate monthly vessel density and speed. We estimated vessel strike risk by multiplying whale density by vessel density corrected by vessel speed. For the BCB population, the highest relative risk was near Utqiaġvik and Prudhoe Bay, Alaska, USA, and near Tuktoyaktuk, Northwest Territories, Canada. For the ECWG population, the highest risk was in the Gulf of Boothia, Cumberland Sound, and near Isabella Bay, Nunavut, Canada. Strike risk was highest in August and September, corresponding with monthly trends in vessel traffic. This study provides important information for focussed monitoring and to minimize/mitigate the threat of vessel strikes to bowhead whales. Although vessel strike risk is presently lower for these populations than for other temperate large cetacean populations, bowhead whale behaviour and projected increases in traffic elevates their risk in the Arctic. Measures to mitigate vessel strike risk to bowhead whales will likely benefit other Arctic marine mammals like beluga and narwhal.

1. Introduction

Many anthropogenic activities cause direct threats to wildlife, but one of the most pervasive, direct impacts globally is collisions between motorized vehicles and animals (Pagany, 2020). Wildlife involved in collisions are injured at a minimum, but collisions often result in death

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https://doi.org/10.1016/j.biocon.2022.109820
Received 6 December 2021; Received in revised form 1 November 2022; Accepted 16 November 2022

(Moore, 2014). The field of terrestrial road ecology has repeatedly demonstrated that the presence of roads, particularly roads with a high volume of traffic, can have population-level impacts on species (e.g., Barrientos et al., 2021). Various mitigation strategies exist for reducing the impacts of roads on wildlife, but the most effective of these involve keeping wildlife off roads (e.g., Glista et al., 2009). Vehicle impacts, however, are not limited to the terrestrial realm, and are similarly widespread in the marine realm (Laist et al., 2001). Marine vessels have frequently been documented colliding with marine animals, large whales (cetaceans) in particular, and these collisions are termed vessel strikes (or ship strikes) (Constantine et al., 2015; Douglas et al., 2008; Vanderlaan and Taggart, 2009). Advances in vessel propulsion technology over the 20th century resulted in faster vessels, paired with the increased number of vessels in the global fleet, has been correlated with an increased number of documented vessel strikes to large cetaceans (Laist et al., 2001).

Large cetaceans, particularly slow swimming baleen whales (mysticetes), are at risk of being struck by ships and other marine vessels (henceforth collectively referred to as vessels), which can lead to serious injury (Laist et al., 2001) and death (Conn and Silber, 2013; Kelley et al., 2020; Vanderlaan and Taggart, 2007). Whales are at greater risk of vessel strike when they spend time at the surface to breathe, rest, forage, and socialize (Parks et al., 2012). Vessel strike risk is elevated at higher vessel speeds, with greatest risk for surfaced whales being within 1–2 whale lengths of the vessel (Silber et al., 2010). Whales below the surface at depths that are 1–2 times the vessel's draft are also at risk, and even more vulnerable, due to the propeller suction effect (Silber et al., 2010). For whale populations, vessel strikes represent a form of additive mortality that is slow to be compensated for due to inherent low reproductive outputs (George et al., 2021; Meyer-Gutbrod and Greene, 2018). A current example is the increase in vessel strikes of North Atlantic right whales (*Eubalaena glacialis*) (Moore et al., 2021), associated with the expansion of their summer foraging range into the Gulf of St. Lawrence (Davies and Brillant, 2019), which has positioned right whales directly within busy shipping lanes (Simard et al., 2019).

Bowhead whales (*Balaena mysticetus*) are endemic to the Arctic, and like many large whales, were greatly reduced to low numbers by commercial whalers from the 15th to 19th centuries (Bockstoce and Burns, 1993; Thewissen and George, 2021). Numbers, however, are rebounding for the two bowhead populations in the North American Arctic, the Bering-Chukchi-Beaufort (BCB) and the Eastern Canada-West Greenland (ECWG) (Givens and Heide-Jørgensen, 2021), and both populations are the target of sustainable subsistence hunts by Inuit (Suydam and George, 2021). Within Canada, both the BCB and ECWG populations are listed as special concern (COSEWIC, 2009; Government of Canada, 2007), and bowheads are listed as endangered in the USA (NOAA, 2022). The BCB bowhead population is estimated to have had a population size of between 6100 and 47,000 animals before commercial whaling (Givens and Heide-Jørgensen, 2021). Two surveys (one from the sea ice, one from the air) were conducted in 2019 to estimate abundance of the BCB population: the ice-based estimate was 14,025 animals (Givens and Heide-Jørgensen, 2021) and the aerial line-transect survey estimate was 17,175 animals (Ferguson et al., 2022); these estimates are not significantly different due to the associated uncertainty (Givens and Heide-Jørgensen, 2021). The ECWG population is estimated to have had 18,000 individuals before commercial whaling (Ferguson et al., 2021), and is now back to 11,747 individuals (95 % confidence interval: 8169 to 20,043) (Frasier et al., 2020). There are, however, numerous emerging threats linked with climate change that already or could have negative influences on population trends, including changes in habitat (e.g., sea ice loss, increased temperature and upwelling frequency, changing current pathways), prey availability and quality (e.g., more temperate-associated forage fish such as capelin (*Mallotus villosus*) and lipid-poor copepods moving north), and predator occurrence (e.g., increased killer whales (*Orcinus orca*) in the Chukchi Sea and Nunavut) (Ashjian et al., 2021; Fortune et al., 2020b; Matthews et al., 2020; Stafford, 2019). Underwater noise from anthropogenic activities, including vessel traffic and offshore energy/mineral exploration and extraction activities, has increased and has significant potential to displace whales from important feeding areas (Halliday et al., 2021, 2020). More vessel traffic also increases the potential for vessel strikes (George et al., 2021, 2017). Bowhead whales are expected to be as vulnerable to vessel strikes as their close relatives, North Atlantic right whales, which have similar body morphology, foraging tactics, slow swimming speed, and prevalence of subsurface foraging behaviour (Fortune et al., 2020b; Parks et al., 2012).

The only studies that have investigated vessel strikes involving bowhead whales found little evidence of past, non-lethal, vessel strikes in subsistence harvested BCB whales (i.e., 1–2 % of whales with scarring from vessels) (George et al., 2017, 1994). However, the more recent analysis relies on data collected from 1990 to 2012 (George et al., 2017), and vessel traffic has increased in the Arctic since that period (Dawson et al., 2018; PAME, 2020). A recent observation from an aerial survey in the Alaskan Arctic documented one bowhead whale carcass with evidence of a vessel strike (Willoughby et al., 2020). Definitively assessing the frequency of lethal vessel strikes is difficult due to the carcasses rarely being encountered, and the ability to determine cause of death in these remote Arctic locations (Harwood et al., 2017a). Unlike in temperate regions, there is no cetacean stranding network collecting detailed observations of stranded cetaceans in the North American Arctic, nor is there an available database of reported vessel strikes from mariners. Vessel strikes pose a welfare issue to whales, since not all strikes are lethal and many whales are severely injured by strikes (Moore, 2014). Strikes can also pose a risk to mariners, including damage to vessels and injuries to humans, particularly for smaller vessels (Schoeman et al., 2020).

Vessel traffic is increasing in the Arctic (Dawson et al., 2018; PAME, 2020) and is projected to continue to increase as the Arctic becomes more reliably ice-free during summer (Li et al., 2021; Mudryk et al., 2021; Smith and Stephenson, 2013; Stephenson et al., 2011). In the Canadian Arctic, for example, vessel traffic nearly tripled in some areas between 1990 and 2015 (Dawson et al., 2018). This increase has been caused by a combination of factors, including resource exploration and extraction, tourism, and shipping (Arctic Council, 2009). More vessel traffic will likely elevate the risk of vessel strikes for bowhead whales. An important step to quantifying risk involves identifying the spatiotemporal overlap between whales and vessels. This analysis may help to inform assessments of population-level consequences of vessel traffic on bowhead whales, and allow conservation and management efforts, such as marine spatial planning, to mitigate those effects.

In this study, we examined the spatiotemporal overlap between vessels and bowhead whales in the North American Arctic (i.e., from Baffin Bay to the Chukchi Sea) during the July–October open-water shipping season. Our main objective was to examine the relative hypothetical risk of vessel strike and identify areas of elevated hypothetical vessel strike risk for BCB and ECWG bowhead whale populations by using vessel tracking data (2012–2018) from the automatic identification system (AIS), and data for bowhead whale distribution (during 2001–2018) obtained through aerial surveys and satellite telemetry. In the Discussion, we examine vessel management strategies that are currently in place and provide recommendations for improved mitigation of vessel strike risk for both bowhead whale populations. This study provides evidence to support conservation actions for bowhead whales, and these actions would likely also benefit other Arctic marine mammals, such as beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*) through reductions in disturbance from vessels.

2. Methods

We obtained four independent datasets from the North American Arctic to estimate relative densities of bowhead whales. Datasets included a satellite telemetry and an aerial survey dataset for each of the two populations (BCB and ECWG) (Table 1). Satellite telemetry and aerial surveys are observation methods with different inherent biases (Caughley, 1974; Douglas et al., 2012; O'Toole et al., 2021). For example, telemetry data provide a long time series for relatively few individuals (>365 days), whereas aerial surveys are a short time series (days) for a larger number of individuals. Therefore, deriving relative density surfaces using both observation methods separately should result in more robust inference than using information from a single method because general trends can be compared between methods. Below, we describe the analytical methods used to derive relative whale densities from each of the four datasets.

2.1. BCB telemetry data

This analysis used telemetry data from 70 BCB whales tagged between 2006 and 2018 with satellite-linked Argos tags (manufactured by Wildlife Computers Inc., Redmond, Washington, USA, and Sea Mammal Research Unit, St. Andrews, UK) at five locations, three in Northwest Territories, Canada: Tuktoyaktuk Peninsula (19 whales), Shingle Point (1 whale), and Herschel Island (1 whale); and two in Alaska, United States: Point Barrow (Utqiaġvik) (46 whales) and St. Lawrence Island (3 whales) (full data collection details available in Citta et al., 2012; Harwood et al., 2017b; Olnes et al., 2020; Quakenbush et al., 2010; Quakenbush and Citta, 2019). The sample of tagged bowhead whales included immature (≤ 13 m, 65 %) and mature (> 13 m; 35 %) whales; however, these proportions varied considerably among sites, seasons, and years, and we did not account for age in this analysis (see references in Table 1). The sample was slightly male-biased (65 % male) based on the 40 whales of known sex (Citta et al., 2021). The raw Argos locations transmitted by the tags were processed using a state-space model (package 'crawl' in R; Johnson and London, 2018; Johnson et al., 2008) to estimate a single position per day for each whale (see methods in Halliday et al., 2021).

2.2. ECWG telemetry data

Telemetry data were also used from 156 ECWG bowhead whales tagged between 2001 and 2016 with satellite-linked Argos tags (Wildlife Computers Inc., Redmond, Washington, USA) during two separate projects, one in Disko Bay, West Greenland, and the other in the eastern Canadian Arctic. In Disko Bay, 98 bowhead whales were tagged between 2001 and 2011 (see details in Chambault et al., 2018). All tagged whales were adults (> 13 m) and 76 % were female based on the 79 bowhead whales of known sex (Chambault et al., 2018). The raw Argos locations from whales tagged in West Greenland were processed using a continuous time multivariate non-Gaussian state space model (as in Albertsen et al. (2015) and Chambault et al. (2018)), and the first location per day per whale was then used for subsequent analyses.

Table 1
General description of four bowhead whale datasets used in this study. Sample size is the number of tagged whales from telemetry data used in this study, whereas number of survey years is the number of years when aerial surveys were conducted. Primary publications are references that can be read for more details about the data collection.

Population	Collection method	Date ranges	Sample size/# survey years	Primary publication (s)
Bering-Chukchi-Beaufort	Satellite telemetry	2006–2018	70 whales	Citta et al., 2012; Harwood et al., 2017b; Olnes et al., 2020; Quakenbush et al., 2010; Quakenbush and Citta, 2019
	Aerial survey	2000–2019	20 years	Clarke et al., 2020
Eastern Canada-West Greenland	Satellite telemetry	2001–2011	98 whales	Chambault et al., 2018
		2003–2016	58 whales	Fortune et al., 2020c; Matthews et al., 2020; Yurkowski et al., 2019
	Aerial survey	2013	1 year	Doniol-Valcroze et al., 2020a

In the eastern Canadian Arctic, 58 bowhead whales were tagged between 2001 and 2016, including 27 whales in Foxe Basin, 27 whales in Cumberland Sound, and four whales in Admiralty Inlet (see details in Fortune et al., 2020c; Matthews et al., 2020; Yurkowski et al., 2019). Most were immature (≤ 13 m; 50 whales, 86 %), 4 were adults (> 13 m; 7 %), and 4 were of unknown lengths. The sample was female-biased (61 % female) based on 51 whales of known sex. The raw Argos locations from whales tagged in the eastern Canadian Arctic were processed using a hierarchical discrete-time correlated random walk state-space model to reduce location error and produce a single location estimate per day for each individual (see Yurkowski et al., 2019 for more details).

2.3. Calculating relative bowhead density from telemetry data

We calculated monthly bivariate normal kernel densities between July and October from the modeled daily positions for each population to estimate the monthly relative densities of bowhead whales in each population. Individuals tagged in the eastern Canadian Arctic and West Greenland were pooled. The kernel densities were created using the R package 'ks' (Duong, 2019) with the standard (i.e., not diagonal) smoother cross-validation bandwidth selector. We imported kernel density rasters (~1 × 1 m resolution) into ArcMap (version 10.4; ESRI, Redlands, California, USA) and resampled the rasters to a 10 × 10 km resolution within the study areas for each population of bowhead whales. Although we applied different modeling methods to analyze each of the bowhead whale telemetry datasets to estimate a single position per day per whale from the raw telemetry data, all methods are leading tools used to reduce location estimate error and refine movement pathways. It is unlikely that these underlying modeled data caused any bias in the output of the kernel density analysis, as we used daily modeled positions per whale to infer monthly relative densities pooled across all individuals, so any daily location differences among the modeling methods would be averaged out across the monthly estimate. While kernel density is a relatively simple method that pools points together without considering autocorrelation or other statistical issues, we have accounted for those issues by preprocessing the individual whale data into one position per day per whale, which has the effect of standardizing the number of points per individual to the greatest extent possible. In all datasets, > 25 % of individual whales had one point for every day of the month, which means that it is unlikely that individual whales would be biasing the analysis. Furthermore, the 10 km resolution of the kernel density output would again remove any spatial bias caused by different methods.

2.4. BCB aerial survey data

Line-transect aerial surveys were flown in the western Beaufort Sea, which involved a portion of the BCB summer range and their fall migration route, during July–October 2000–2019 as part of the Aerial Surveys of Arctic Marine Mammals (ASAMM) project (full methodological details are available in Clarke et al. (2020)) (Fig. 1). Transects were spaced 19 km apart, based on a grid with a randomly selected starting point. Transects were oriented perpendicular to the coastline, to cut across isobaths, from shore to beyond the 2000-m isobath. Surveys were flown in de Havilland Twin Otters and North American Rockwell Turbo Commanders; both models are twin turbine aircraft with bubble windows on the left and right sides, allowing unobstructed views from the horizon to the transect directly beneath the aircraft. Surveys were

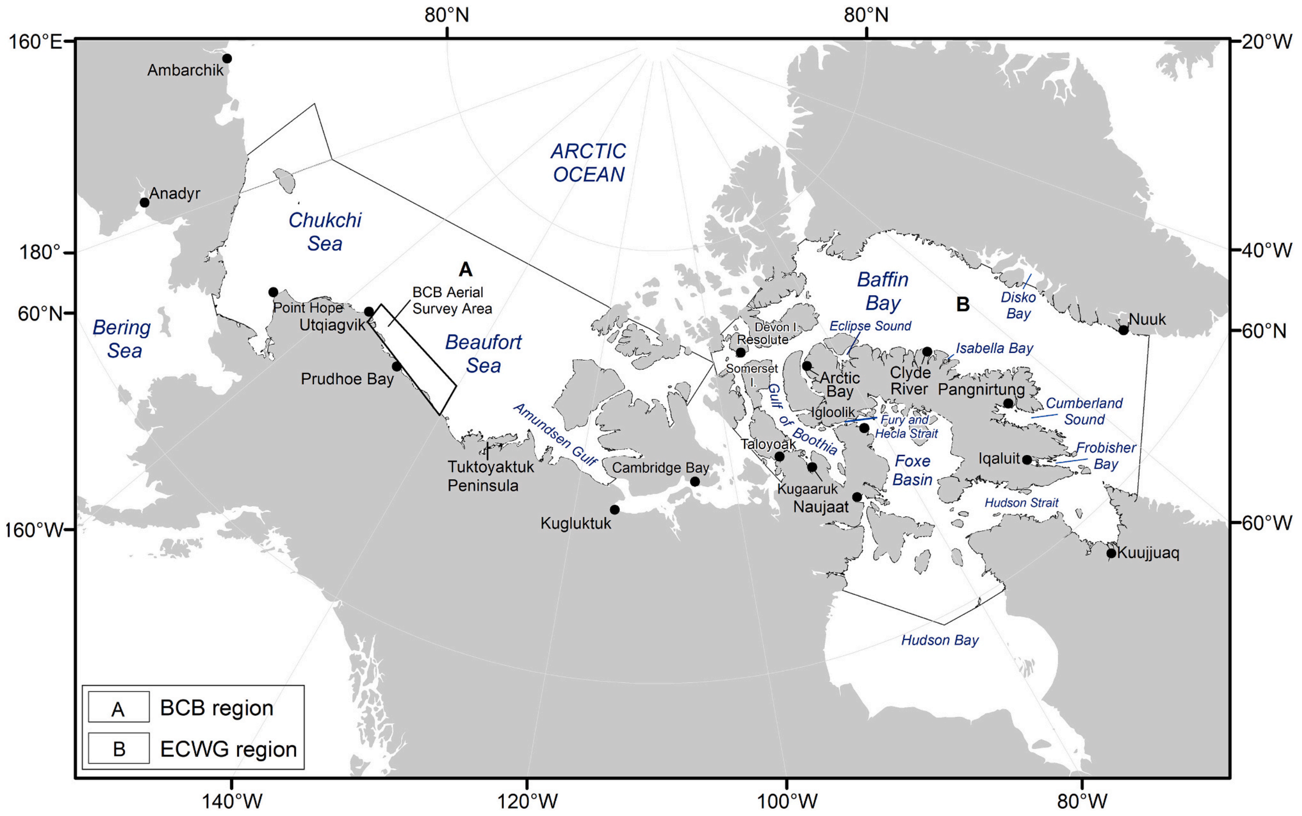

Fig. 1. Map of the North American Arctic study area, delineating the spatial coverage of the Bering-Chukchi-Beaufort (BCB) bowhead telemetry data (A), Eastern Canada-West Greenland (ECWG) bowhead telemetry data (B), and the BCB bowhead aerial surveys. The ECWG bowhead aerial survey tracks are shown in Fig. S1.

flown 305–460 m above the sea surface, at 213 km/h survey speed. Each survey team was comprised of two primary observers and one dedicated data recorder.

The monthly (July to October) relative density for the BCB population was calculated based on sightings from the ASAMM data during 2000–2019. Full details are presented in Clarke et al. (2020), and the primary outputs of this analysis are displayed in Fig. 23 of Clarke et al. (2020). This analysis includes survey effort but does not account for availability or perception bias. In brief, the western Beaufort Sea survey area was partitioned into 5 × 5 km grid cells. Two quantities, the total survey effort and the total number of whales sighted, were summed across years for each month-cell combination. Bowhead whale relative density was then smoothed across the study area using a generalized additive model (GAM) with a negative binomial distribution and a natural logarithmic link function in R package ‘mgcv’ (Wood, 2017). The GAM used only spatial covariates (projected longitude and latitude) as the predictor variables. The predicted relative density of bowheads in each month between July and October across 2000–2019 was then saved as a raster with 5 × 5 km resolution. To match other analyses, we converted the raster resolution to 10 × 10 km in ArcMap (version 10.4, Esri, West Redlands, California, USA).

2.5. ECWG aerial survey data

Aerial surveys were conducted in the eastern Canadian Arctic in August 2013 as part of the multi-species High Arctic Cetacean Survey (full methodological details are available in Doniol-Valcroze et al. (2020b, 2020a). All ECWG bowhead whales observed during the survey were counted using line-transect protocols. Transect locations were selected to cover a wide range of locations for both bowhead and narwhal throughout Nunavut based on high-abundance locations identified by previous telemetry data, aerial surveys, and traditional knowledge (Fig. S1). Surveys were flown using three de Havilland Twin Otter aircraft traveling separate transects at an altitude of 305 m and a speed of 185 km/h. Four visual observers were located at the bubble windows (two per side), and a fifth team member acted as a navigator for each aircraft. All bowhead sightings were corrected for observer bias, then counted within 10 × 10 km grid cells. Sightings were not corrected for survey effort or availability bias (i.e., submerged individuals). This count represents the relative density of bowhead whales in August 2013.

2.6. Satellite AIS vessel data processing

Satellite automatic identification system (AIS) data from 2012 to 2018 were provided by exactEarth (Cambridge, Ontario, Canada). AIS locations were converted to track lines for each individual vessel. We grouped AIS records by vessel class because different vessel classes tend to travel at different speeds (Figs. S8, S11). The classes that we used were bulk carriers, container ships, cruise ships, ferries, fishing vessels, government vessels (including coast guard ships, ice breakers, and other research ships), navy vessels, pleasure craft (private yachts, sailboats, small boats, and other recreational boats), tanker ships, and tugboats. AIS is mandatory for large commercial vessels ≥300 gross tonnes on international voyages, cargo ships ≥500 gross tonnes on domestic voyages, and all passenger ships of any size (International Maritime Organization, 2014). Many other vessels carry AIS transponders for safety reasons, even when they are not mandatory, particularly in the Arctic. However, there are still vessels that do not carry AIS transponders at all and others that have AIS transponders but turn them off (Halliday et al., 2018), which means that our vessel densities are underestimates, especially for certain vessel classes like pleasure craft, cruise ships, and tug boats. We summed the number of times that individual vessel tracks in each vessel class crossed each 10 km grid cell in each month of each year (Figs. S7, S10). This metric is therefore not a count of the number of unique vessels within a cell, but rather a count of the level of traffic within the cell. For each vessel class, we calculated the mean number of vessel tracks per grid cell per month across years to obtain one vessel density value per month for each grid cell for the entire study period. We also calculated the mean vessel speed for each vessel class within each 10 km grid cell per month, while excluding vessels with speeds <1 knot (because those vessels likely were not moving) and vessels with speeds >40 knots (because those speeds are unrealistic and likely represent data errors).

2.7. Hypothetical vessel strike risk calculation

Prior to calculating hypothetical vessel strike risk, all four bowhead whale relative density datasets were normalized between zero and one by dividing each cell value by the maximum possible value for each dataset. This procedure standardized the output for interpretation and comparison of areas, since a whale density value of one equals the highest relative density within that dataset, and a value of zero is an area with no bowheads. Vessel strike risk was calculated in two steps. First, the overlap between bowhead whales and vessels within each class was calculated by multiplying the normalized bowhead whale density per cell by vessel density per cell. Second, overlap was corrected by vessel speed per vessel class, since increased vessel speed can increase the chance of a vessel strike being lethal. The overlap between bowhead

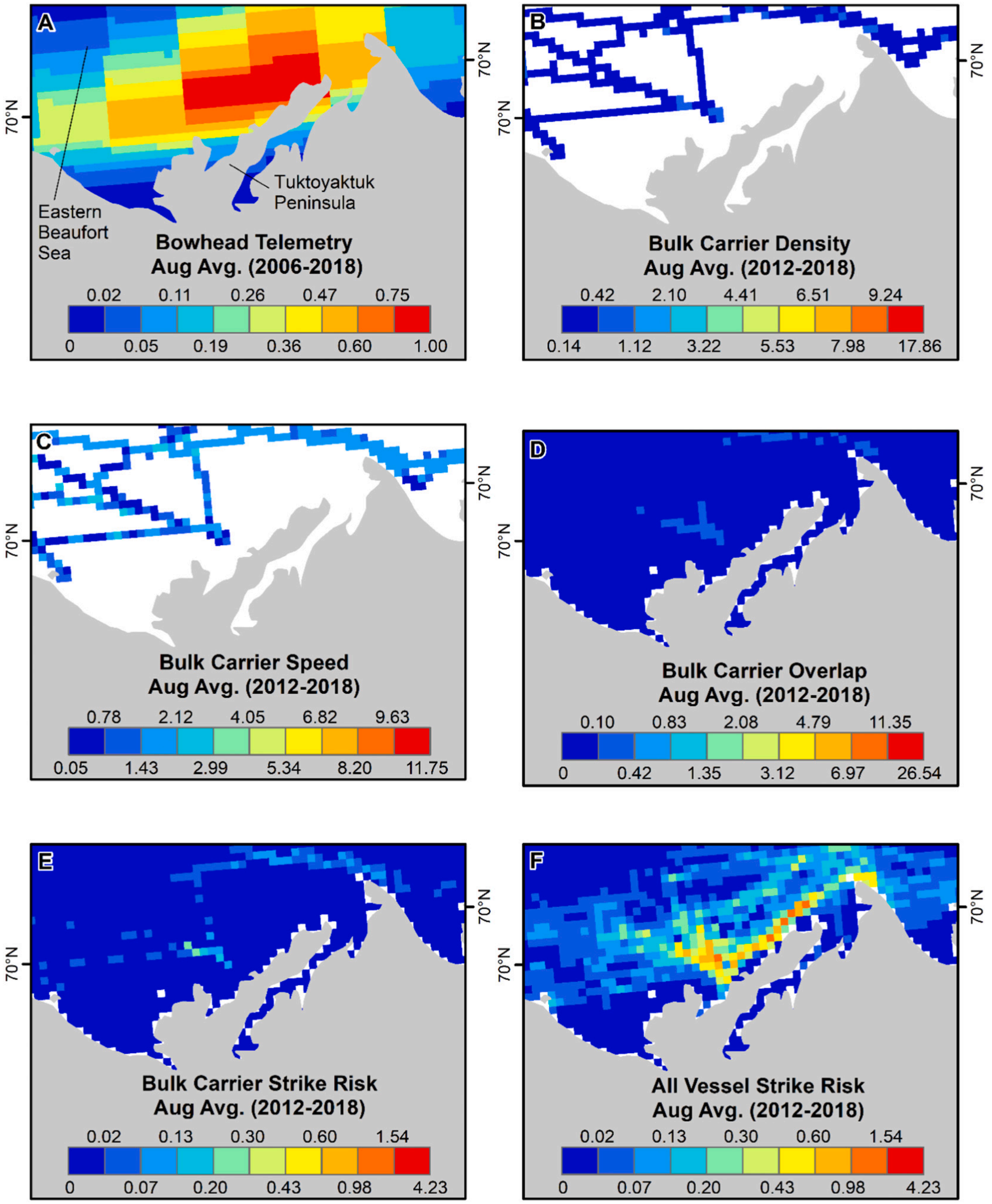

Fig. 2. Example data processing steps for the Bering-Chukchi-Beaufort bowhead whales in August in a subset of the study area near Tuktoyaktuk Peninsula. The panels show one month of bowhead whale relative density from telemetry data (A), one month of vessel density for one vessel class (bulk carriers) (B), vessel speed for one vessel class (bulk carriers) (C), overlap for bulk carriers and bowhead whales (D), hypothetical vessel strike risk for bowhead whales based on bulk carriers (E), and vessel strike risk across all vessel classes (F). A and B are multiplied to derive D, and D is corrected by C to derive E. F is the sum of all vessel classes derived using the same approach as E for bulk carriers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

whales and vessels corrected by vessel speed essentially weights the overlap values, such that higher values represent a greater relative vessel strike risk. We corrected the overlap values for each vessel class separately by applying the equation developed by Vanderlaan and Taggart (2007) based on lethal vessel strike data available for all species of large whales. This equation relates the risk of a strike being lethal (P_L) to vessel speed (v) in knots:

$$P_L = \frac{1}{1 + exp^{-(-4.89+0.41\ v)}} \quad (1)$$

We opted to use this relationship rather than the similar relationship developed by Conn and Silber, 2013) because eq. 1 gives $P_L = 0$ when vessel speed is 0 kts, whereas Conn and Silber's relationship still has a $P_L = 0.13$ when speed is 0 kts. Otherwise, the two relationships have similar shapes and predictions. Vessel strike risk values for each vessel class were then summed across vessel classes to calculate the overall vessel strike risk. An example of the steps to calculate vessel strike risk is shown in Fig. 2 with BCB telemetry data from August.

The vessel strike risk score can vary between zero (either no vessels or no bowhead whales in a cell) and the maximum vessel density value within a region, if that maximum vessel density also overlapped with maximum bowhead whale relative density and the average vessel speed was >20 knots (see relationships in Fig. 3). When examining vessel strike risk results, we are specifically interested in identifying hotspots for vessel strike risk. Hotspots, in this case, refer to grid cells with elevated strike risk compared to some value. A large majority of grid cells in these datasets will have a vessel strike risk value of zero, simply because either no vessels or no bowhead whales were in that cell, and these cells with zero risk bias the average towards zero. However, the 95th percentile is a useful comparison point, since the hotspots can simply be defined as grid cells where the vessel strike risk is in the top 5 % of all values. These values vary between the four datasets, and are much lower for the telemetry data compared to the aerial survey data. The 95th percentile for the BCB aerial survey vessel strike risk is 0.16, whereas it is 0.23 for the ECWG aerial survey. We therefore use a conservative value of 0.3 to define the vessel strike risk hotspot, where any cells with values ≥0.3 can be considered a hotspot.

We do not statistically compare results between survey methods, months, or populations because our methodology biases the absolute numbers for each of these categories, making statistical comparisons meaningless. For example, the specific kernel density values will vary depending on the number of whale points going into the analysis, and given that the two populations had different numbers of whales tagged, it means that kernel density values are not comparable. Although we normalized these values between 0 and 1, a 1 for the BCB will not be the same as a 1 for the ECWG. Given that these normalized whale densities are then the basis of the strike risk calculation, we cannot compare between them. The same logic applies to monthly comparisons even within a population, and similarly, between the aerial survey and telemetry data.

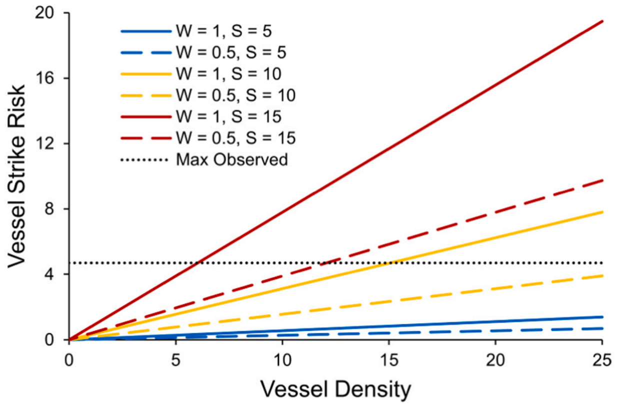

Fig. 3. Relationship between hypothetical vessel strike risk and relative bowhead whale density, vessel density, and vessel speed. The bowhead whale density (W) and vessel speed (S) are denoted in the legend. The maximum observed vessel strike risk value in this study is also denoted by the dotted black horizontal line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Not all vessels are equally likely to cause a lethal strike, even when traveling the same speeds, due to differences in size, draft, and tonnage (e.g., Rockwood et al., 2018). We therefore also calculated the vessel strike risk using two additional subsets of vessel classes: first, with all vessel classes except pleasure craft (thereby excluding the smallest vessels); and second, only with large merchant vessels (bulk carriers, container ships, and tanker ships), which are the largest vessel classes that are most likely to cause a lethal strike.

Not all vessel encounters are assumed to be strikes; rather, with increasing vessel density and increasing vessel speed, there is an increased risk of a vessel strike occurring. This is why we refer to our calculations as strike risk. Vessel strike risk values will also not be fully comparable across the four bowhead whale datasets, because values of relative bowhead whale density were normalized between zero and one, yet a value of one could represent a much higher density in one dataset versus another, and the telemetry data were based on a kernel density of telemetry data rather than on underlying count data.

3. Results

3.1. Bering-Chukchi-Beaufort bowheads

The distribution of the BCB, based on telemetry data, shifts westward from July to October (Fig. S2). In July, bowhead whales are mainly within their main summer range in the eastern Beaufort Sea and Amundsen Gulf. They begin their autumn westward migration through the Alaskan Beaufort Sea in August, moving farther west into the Chukchi Sea in September, and are wholly within the western Beaufort Sea and Chukchi Sea in October. Aerial survey data for the western (Alaskan) Beaufort Sea reflect this pattern (Fig. S3), with bowheads distributed farther east during July, spreading throughout the Alaskan Beaufort in both August and September, then mostly found in the western Beaufort during October.

Vessel traffic was elevated in the southern Chukchi Sea near the Bering Strait during all months of the study (July–October; Fig. S6). Near Prudhoe Bay in the mid-Alaskan Beaufort Sea, vessel traffic was also relatively high from July through October; however, vessel traffic in the eastern Alaskan Beaufort and western Canadian Arctic was highest in August and September.

Hypothetical vessel strike risk based on BCB telemetry data was low in July, with only a few cells with values greater than zero, except around Prudhoe Bay where six cells had values >0.10, only two cells >0.3, and with a maximum value of 0.75 (Fig. 4). Vessel strike risk was highest during August and September, generally within 100 km of the coastline throughout the Beaufort Sea, with risk hotspots (i.e., defined here as areas of elevated risk with values >0.3) near Tuktoyaktuk, Prudhoe Bay, and Utqiaġvik, and with some elevated risk in the southern Chukchi Sea in August. In October, a few cells had elevated risk near Prudhoe Bay, northwest of Point Barrow, and near the community of Kivalina in the southeast Chukchi Sea. August had 606 cells with values >0.10, 133 cells >0.30, 55 cells >0.50, and 11 cells >1.0, and the maximum cell value was 1.50. Similarly, September had 558 cells with values >0.10, 77 cells >0.30, 15 cells >0.50, and three cells >1.0, and the maximum cell value in this month was 2.25. In October, 100 cells had values >0.10, two cells >0.30, and the maximum value was 0.55. With values pooled across months, the median cell value was 0, the mean was 0.008, the 75th percentile was 0.001, and the 95th percentile was 0.03, which means that most cells within the area determined by BCB telemetry data to contain bowhead whales have no strike risk because no vessels were present in large areas offshore in the Beaufort

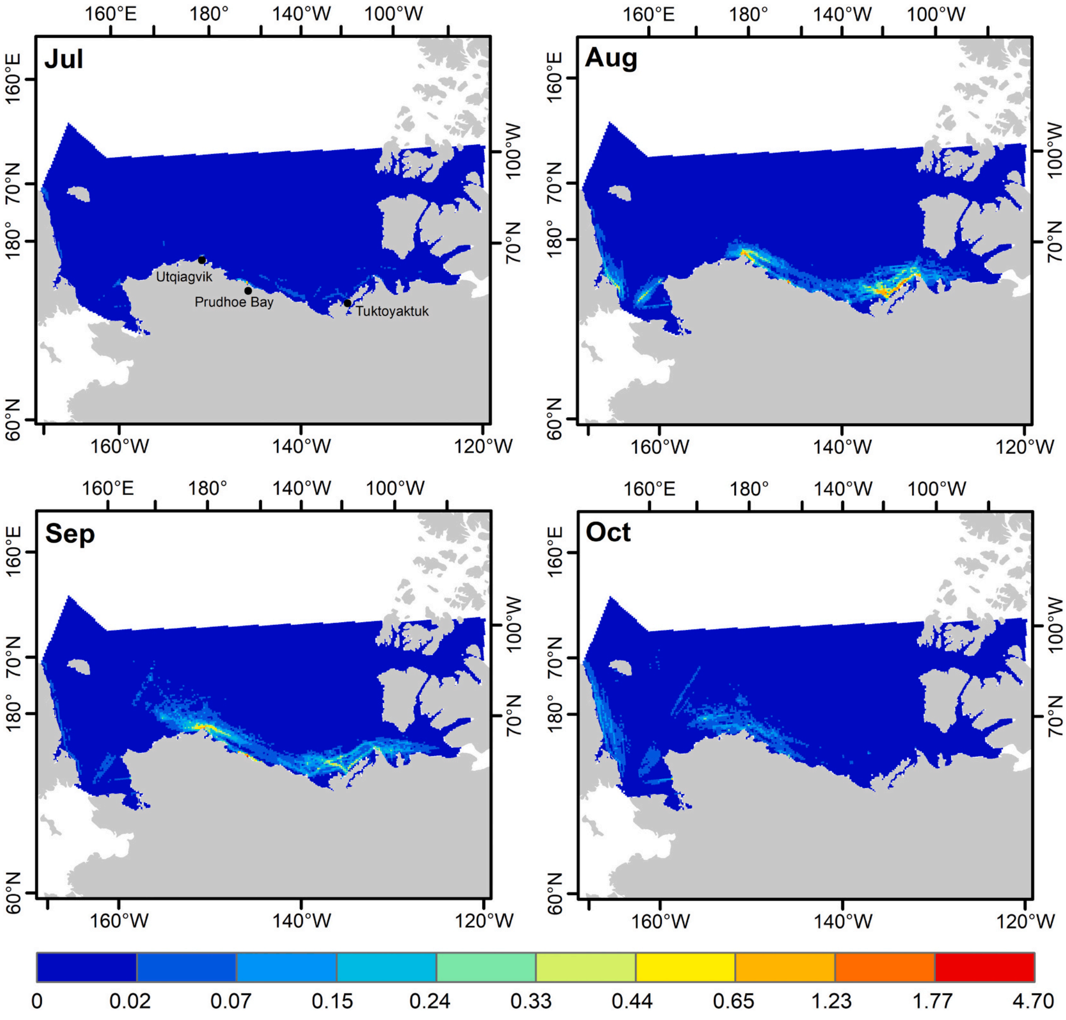

Fig. 4. Hypothetical vessel strike risk for Bering-Chukchi-Beaufort bowhead whales based on telemetry data in July, August, September, and October. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Chukchi seas. For the BCB telemetry data, vessel strike risk values >1 were only seen at Prudhoe Bay from July through September, near Tuktoyaktuk in August, and near Utqiaġvik in August and September.

The vessel strike risk based on BCB aerial survey data, which is only available for the western (Alaskan) Beaufort, was low (all cells <0.15) in July, elevated close to the coast between Prudhoe Bay and Utqiaġvik in August and September (many cell values >0.15), and reduced in October when the highest values were near Prudhoe Bay (Fig. 5). In August, 142 cells were > 0.10, 44 cells were >0.30, 30 cells were > 0.5, and 11 cells were > 1.0, with the maximum value of 3.40. In September, 103 cells were > 0.10, 23 cells were > 0.30, 13 cells were >0.50, and 5 cells were >1.0, with a maximum value of 4.70. In October, only nine cells were >0.10, and only one cell was >0.15, with a maximum value of 0.81. With values pooled across months, the median cell value was 0.005, the mean was 0.04, the 75th percentile was 0.03, and the 95th percentile was 0.16. The BCB aerial survey area was smaller in size than the BCB telemetry survey area, and this translated into a lower proportion of cells with no vessels, compared to the vast BCB telemetry area. This produced higher absolute values of risk for the survey area, but we note that the locations of elevated vessel strike risk were similar using both methods.

3.2. Eastern Canada-West Greenland bowheads

Areas of relatively high ECWG density were generally consistent between July and October, although they tended to become more concentrated in September (Fig. S4). There were three main areas of concentration, which were identified through both telemetry and aerial surveys: 1) in the Gulf of Boothia and northern Foxe Basin; 2) in Cumberland Sound; and 3) along the east coast of Baffin Island near Clyde River and Isabella Bay. These three locations with higher bowhead density were also identified by the aerial surveys that occurred in August 2013 (Fig. S5).

Vessel traffic within the ECWG bowhead whale range was fairly high along the coastline of West Greenland from July through October, but remained fairly diffuse throughout most of Baffin Bay and Nunavut. Certain key routes had repeated vessel passages, such as: through Hudson Strait, northern Hudson Bay, and Frobisher Bay from July through October; in Eclipse Sound and Gulf of Boothia in August and September; and along southern Devon Island in August (Fig. S9). Based on the vessel data used in this study, the only 10 × 10 km cells within the eastern Canadian Arctic that had >17 vessel passages per month were in Eclipse Sound in August and September. The other key travel routes previously mentioned all had cells with >5 vessel passages per month, on average.

The hypothetical vessel strike risk for ECWG based on telemetry data was relatively low throughout their range, with vessel strike risk hotspots in the Gulf of Boothia and near Isabella Bay and Clyde River in August and September, and in Cumberland Sound near Pangnirtung from August through October (Fig. 6). In the Gulf of Boothia, the main area with elevated vessel strike risk was near the south end of Somerset Island in August, whereas in September it was farther south near the

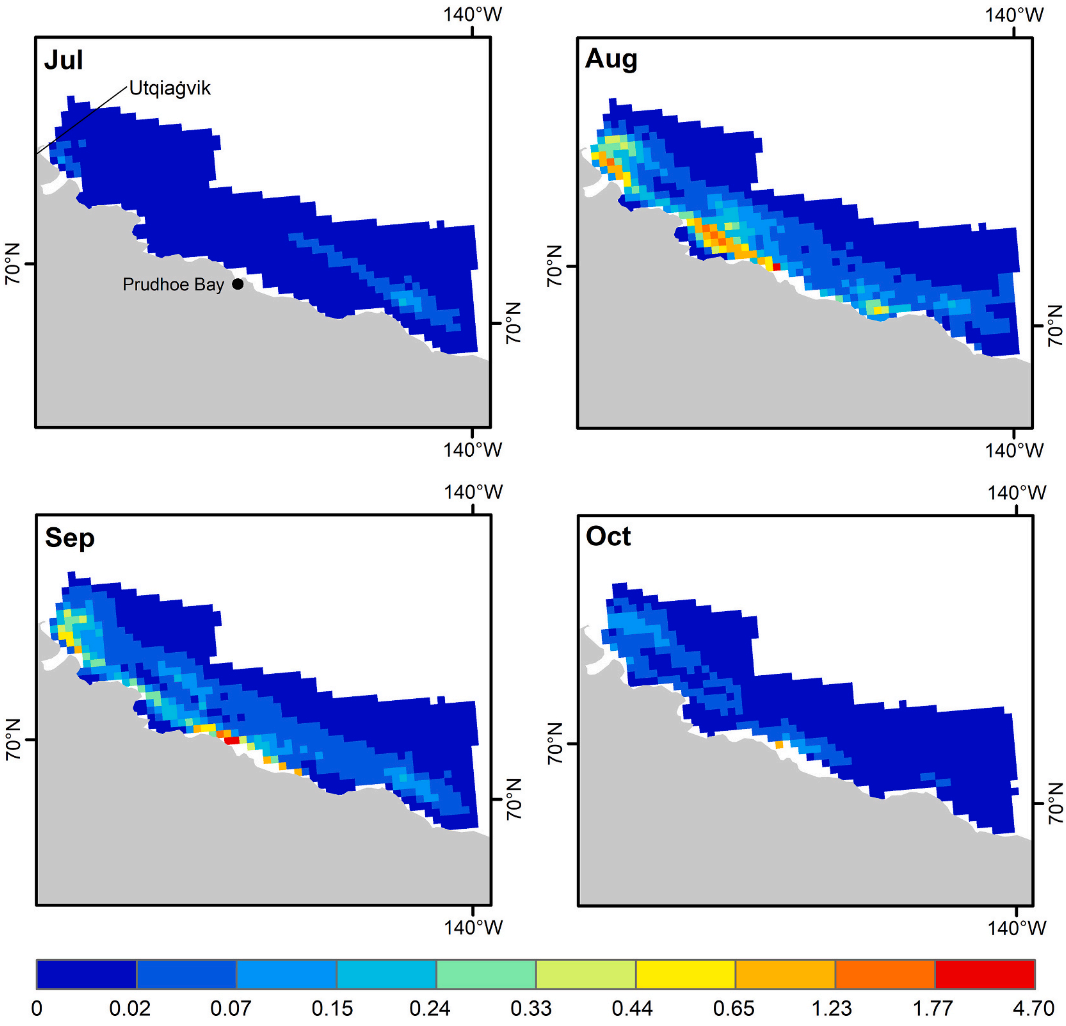

Fig. 5. Hypothetical vessel strike risk for Bering-Chukchi-Beaufort bowhead whales based on aerial survey data in July, August, September, and October. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

community of Kugaaruk and into Fury and Hecla Strait and northern Foxe Basin. Along eastern Baffin Island, the areas with greatest risk were near Clyde River and Isabella Bay in August, whereas in September, the high risk area was concentrated offshore of Isabella Bay only. The vessel strike risk hotspot in Cumberland Sound remained fairly consistent between August and September, and was centred around the community of Pangnirtung. In October, two cells within Hudson Strait were also above the threshold to be considered a vessel strike risk hotspot. In the three main areas with hotspots, September was the month with peak risk (Fig. 6). In July, only 69 cells were > 0.10, and the maximum value was 0.18. In August, 146 cells were > 0.10, 12 cells were > 0.30, and only one cell was >0.50, with a maximum value of 0.51. In September, 201 cells were > 0.10, 30 cells were > 0.30, 12 cells were > 0.50, and only one cell was >1.0, with a maximum value of 1.10. In October, 177 cells were > 0.10, 15 cells were > 0.30, and six cells were > 0.50, with a maximum value of 0.82. With values pooled across months, the median cell value was 0, the mean was 0.003, the 75th percentile was 0.00005, and the 95th percentile was 0.012. Similar to the BCB telemetry data, the ECWG telemetry data had a large proportion of cells with a vessel strike risk value of zero, due to the lack of overlap between vessels and bowhead whales in those cells.

Vessel strike risk based on the ECWG aerial survey data, which was only available for the month of August, similarly showed increased risk in the Gulf of Boothia, Cumberland Sound, and near Isabella Bay, with the highest cell values in Gulf of Boothia and Cumberland Sound (Fig. 7). The aerial survey covered 45 cells, and of these, only five had values >0.10, two were > 0.30 (and both of these also >0.50), and the maximum was 0.82. The median cell value was 0.002, the mean was 0.05, the 75th percentile was 0.03, and the 95th percentile was 0.23.

3.3. Hypothetical vessel strike risk as a function of vessel class

When we excluded pleasure craft from the calculation of hypothetical vessel strike risk, the identified hotspots were identical and the cell values remained largely unchanged for both BCB and ECWG bowhead whales (Figs. S16, S17). Therefore, pleasure craft had little impact on the calculation of vessel strike risk. This is likely because most pleasure craft in our study region traveled at low speeds (< 10 knots), particularly in the BCB region (Figs. S8, S11).

Focusing the calculation of vessel strike risk only on bulk carriers, container ships, and tanker ships, the outputs changed significantly (Figs. S16, S17). Although all previously identified risk hotspots continued to have some elevated risk based on these three vessel classes, the magnitude of risk decreased. For BCB in particular, the vessel strike risk decreased because few vessels within those classes traveled through whale concentration areas. For ECWG, the area off eastern Baffin Island near Clyde River and Isabella Bay remained an area of higher vessel strike risk, particularly in September, as did the area in Cumberland Sound closest to Pangnirtung. Much of the vessel strike risk in the Gulf of Boothia, particularly during August near southern Somerset Island, all

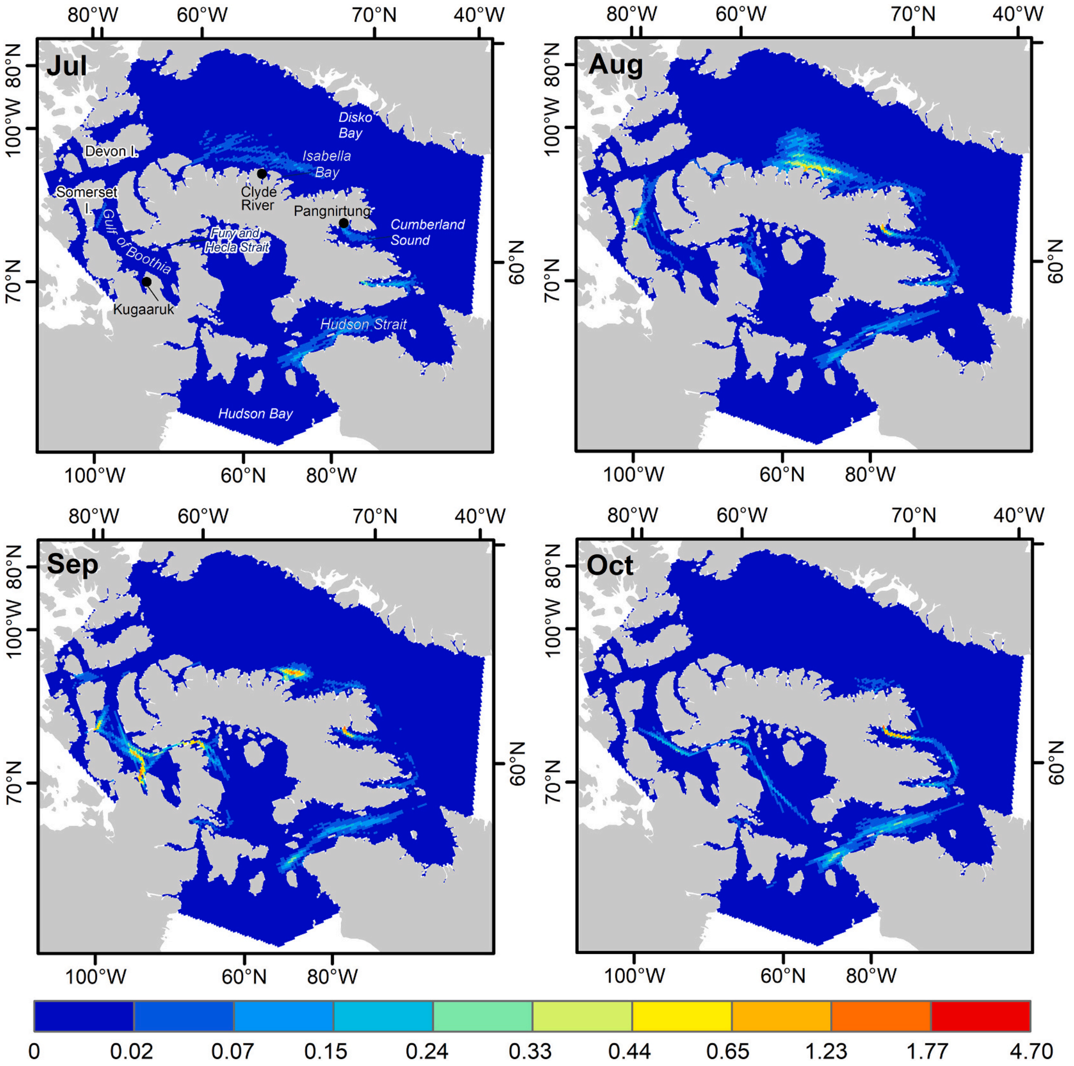

Fig. 6. Hypothetical vessel strike risk for Eastern Canada-West Greenland bowhead whales based on telemetry data in July, August, September, and October. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but disappeared, whereas risk decreased but was still present during September in the southern Gulf of Boothia compared to the calculations that included all vessel classes.

As a final step in this analysis, we extracted the average number of vessel tracks across years within each vessel class in September that contributed to the vessel strike risk hotspots (values >0.3) for each 10 km cell, and then summed the number of vessel tracks per class across cells (Fig. 8).

For the hotspot at Utqiaġvik, tug boats were the most common class. The next most common vessel class was fishing vessels (many of which are research vessels), which were less than half as common as tug boats. Most other vessel classes were still relatively common, but tanker ships and ferries were the least common. For the hotspot near Tuktoyaktuk, tug boats were also by far the most common vessel class. Government vessels, tanker ships, and fishing vessels also occurred multiple times per year, whereas other classes were quite rare, and ferries were entirely absent.

In the Gulf of Boothia, government vessels were the most frequent vessel class, followed by tanker ships. Tug boats and fishing vessels were entirely absent, container ships and navy vessels were rare, and other vessel classes had a few vessels per year contributing to this hotspot. The hotspot near Isabella Bay was most commonly frequented by tanker ships and bulk carriers, but all other classes except tug boats were common. Tug boats were entirely absent from this hotspot. The hotspot in Cumberland Sound is driven by relatively low levels of bulk carriers, cruise ships, government vessels, and recreational boats, and very low levels of ferries and tanker ships. Container ships, fishing vessels, navy ships, and tug boats were entirely absent from this site.

4. Discussion

Combining whale distribution data and vessel density data has allowed us to identify multiple hotspots for hypothetical vessel strike risk (i.e., areas of elevated risk) for both the Bering-Chukchi-Beaufort (BCB) and Eastern Canada-West Greenland (ECWG) populations of bowhead whales in the North American Arctic. Our analysis was conducted at the temporal resolution of one month, based on pooled vessel data spanning 2012 through 2018, and four bowhead whale datasets collected at different periods between 2000 and 2019. Most of the vessel strike risk hotspots were consistently identified by both the bowhead whale satellite telemetry and aerial survey data.

For BCB whales, hotspots for vessel strike risk were identified in the Alaskan Beaufort Sea from August through October near Utqiaġvik and Prudhoe Bay and in the Canadian Beaufort Sea near Tuktoyaktuk in August and September. For ECWG, hotspots for vessel strike risk were identified in four areas: 1) Gulf of Boothia at the south end of Somerset Island in August; 2) Gulf of Boothia near Kugaaruk and Fury and Hecla Strait in September; 3) along the eastern coast of Baffin Island near

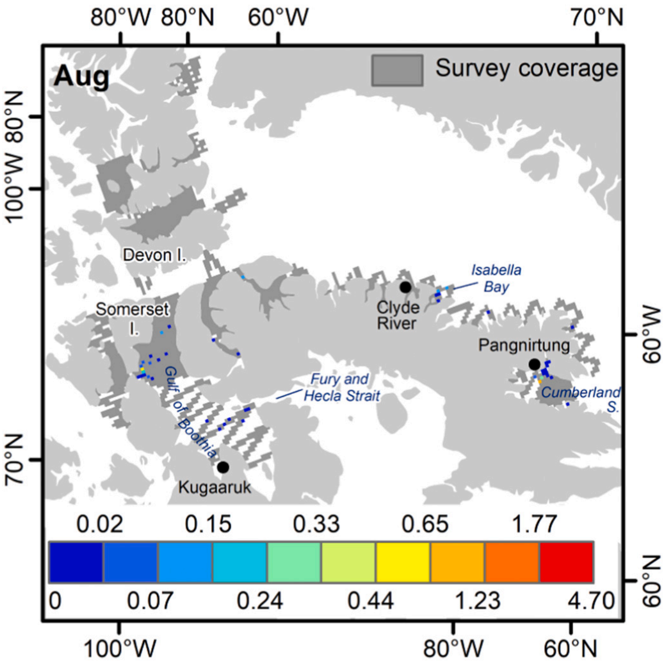

Fig. 7. Hypothetical vessel strike risk for Eastern Canada-West Greenland bowhead whales based on aerial survey data in August. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Clyde River and Isabella Bay in August and September; and 4) in Cumberland Sound near Pangnirtung from August through October.

In all cases, the greatest potential for vessel and whale overlap occurred in areas where relatively large numbers of bowhead whales congregate (Figs. S2-S5) and where vessels tend to use the same transit routes (Figs. S6, S9). Areas where bowhead whales congregate are likely related to foraging activity (Finley, 1990; Fortune et al., 2020a; Harwood et al., 2017b; Olnes et al., 2020), which increases the risk of vessel strike given that bowhead whales forage close to the surface at times (Fortune et al., 2020b) and may continue foraging even when a vessel is nearby (Wartzok et al., 1989). Vessels follow similar paths in these regions for a variety of reasons. In some locations, vessels follow restricted routes in narrow waterways. This type of geographically restricted route occurs in the Gulf of Boothia where vessels transit south of Somerset Island, and in Fury and Hecla Strait. Near communities, vessels tend to follow similar routes. These community traffic routes occurred near Tuktoyaktuk, Kugaaruk, Clyde River, and Pangnirtung. In the case of vessels transiting long distances, many tend to travel close to the coast. Coastal routes are often used in the Beaufort Sea to reduce the potential of encountering sea ice. Some vessels coming from the Chukchi Sea are destined for Utqiaġvik and others for the eastern Beaufort Sea, causing routes to converge near Point Barrow. Finally, resource extraction activities can lead to increased concentration of vessel traffic. This is the case in Milne Inlet and Eclipse Sound from Baffinland's Mary River Mine, in the Alaskan Beaufort Sea near the Prudhoe Bay oil and gas operations, and in other areas of the Chukchi and Beaufort seas where oil and gas exploration activities have taken place.

Our study used two different observation methods, satellite telemetry and aerial surveys, to calculate relative density of bowhead whales

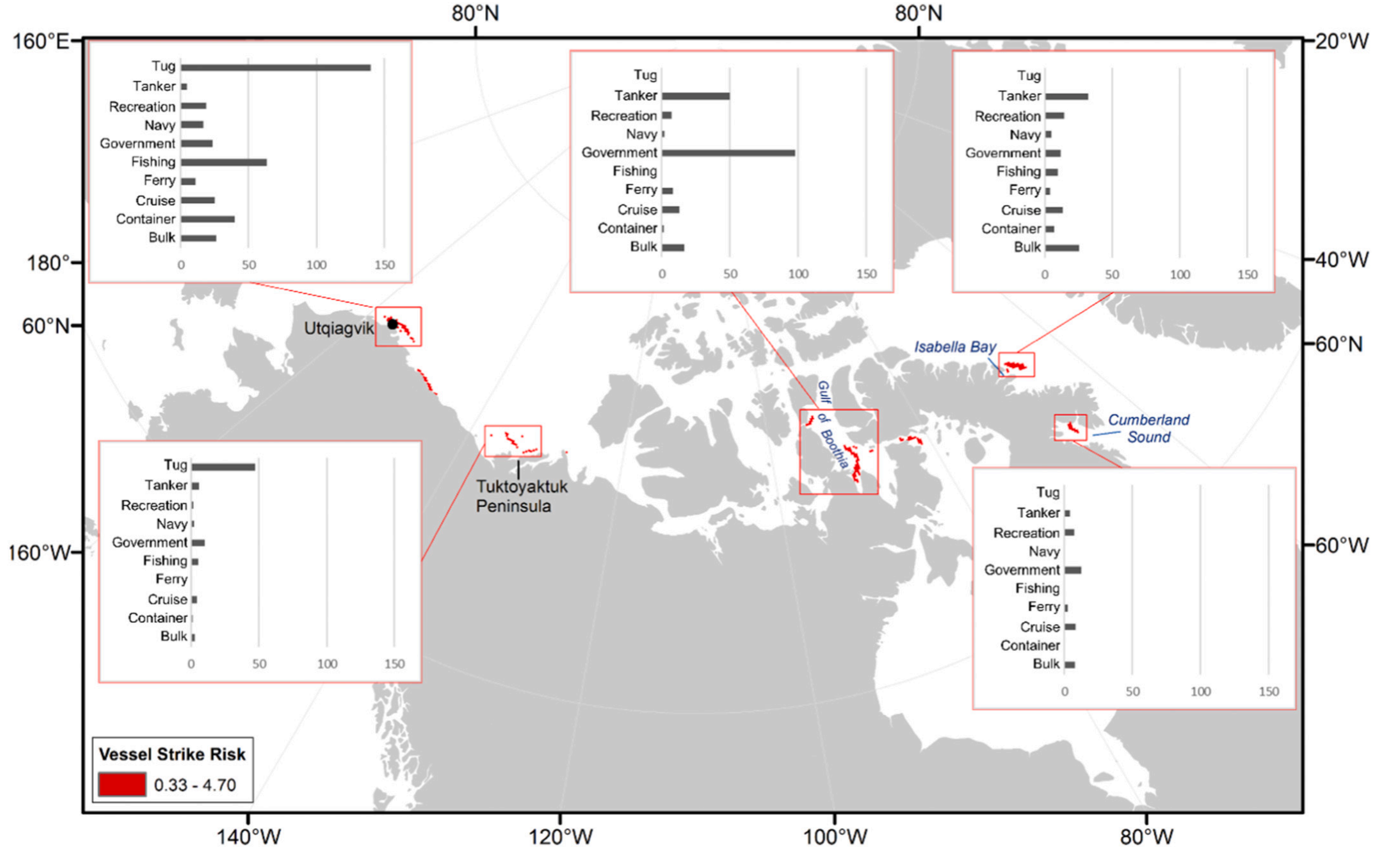

Fig. 8. Average number of vessel tracks per year between 2012 and 2018 in different vessel classes contributing to hypothetical vessel strike risk in September at the hotspots for Eastern Canada-West Greenland bowhead whales (Cumberland Sound, Isabella Bay, and Gulf of Boothia) and at the hotspots for Bering-Chukchi-Beaufort bowhead whales (Tuktoyaktuk and Utqiaġvik). Red cells on the map show all 10 × 10 km cells for September above a vessel risk strike value 0.33. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for our predictions of hypothetical vessel strike risk. By considering both methods, we were able to qualitatively compare patterns of whale habitat use and therefore the role of survey method in determining vessel strike risk. Results based on telemetry and aerial survey data generally agreed, each identifying the same hotspots for vessel strike risk, thereby providing confidence in the geographic locations of the risk areas identified. However, each observation method has inherent biases which must be considered when interpreting the results. The BCB telemetry data, for example, contained a large proportion of immature whales (65 %). Immature whales frequent the shallow shelf waters of the eastern Beaufort Sea, whereas mature whales tend to use deeper waters of the Amundsen Gulf (Koski et al., 1988). Consequently, mature whales were under-represented in the tagging sample for the western Canadian Arctic portion of their range (Harwood et al., 2017b), and the habitats they use that overlap with shipping routes through Amundsen Gulf in summer and autumn are also likely under-represented. Similarly, ECWG telemetry data from whales tagged in Disko Bay was mostly adult females (Chambault et al., 2018) and Cumberland Sound was almost entirely immature whales (Fortune et al., 2020c), which may cause biases within each of those datasets. The aerial survey data used for BCB bowhead whales only covered the Alaskan Beaufort Sea, comprising only a portion of the population's summer and autumn range; however, the strength of this dataset is that it captured both seasonal and annual variability, given surveys were done July to October across two decades. By contrast, the aerial survey data for ECWG represented only a single month in a single year. However, ECWG aerial survey had the advantage of covering most of the ECWG summer range, with the exception of some anticipated low density areas in Hudson Bay and Hudson Strait.

This analysis was based on average vessel density between 2012 and 2018. There has generally been an increasing trend in vessel traffic over time during our study period throughout the Arctic (PAME, 2020) and in the Northwest Passage in particular (PAME, 2021). The increase in vessel traffic specifically in Baffin Bay is large, with a 160 % increase in bulk carrier traffic between 2013 and 2019 that is directly caused by traffic to Baffinland's Mary River Mine (PAME, 2020). Much of this increased traffic travels through the bowhead whale concentration area near Isabella Bay and Clyde River. If more recent data were available, an annual analysis could conceivably show increased risk for ECWG in recent years due to the increased traffic in Baffin Bay. Conversely, the Governments of Canada and the United States began a five-year moratorium on new oil and gas licences in the Arctic in 2016 (Government of Canada, 2016), which effectively led to a decrease in vessel traffic related to oil and gas developments in the Chukchi and Beaufort seas in subsequent years. Therefore, an annual analysis of vessel strike risk might show reduced risk for BCB whales in more recent years compared to some of the earlier years (such as in 2017) when oil and gas activities were more widespread (Halliday et al., 2021).

The spatiotemporal distributions of vessel traffic and of bowhead whales should be monitored to determine whether the patterns identified here persist or shift, or if spatiotemporal variability in hypothetical vessel strike risk occurs at finer temporal scales than the averaged monthly resolution considered here. Continued monitoring of bowhead whales, through both aerial surveys and telemetry, will allow for more precise estimates of bowhead whale density and allow for assessments of how monthly distributions may shift through time. In particular, increasing the number of bowhead whales tagged within a year would improve our capability to assess changes in distribution and annual variability. Similarly, more frequent aerial surveys covering the full summer range of each population of bowhead whales would contribute to monitoring of habitat use patterns for each population. For vessel traffic, the quality of satellite AIS data has improved in recent years, therefore this data source is good for tracking vessels with an AIS signal. However, given that numerous vessels do not carry AIS transponders, including a large number of pleasure craft (Halliday et al., 2018), more work needs to be done to quantify the extent, types, and timing of marine vessel traffic through these waters. This could include creating incentives to increase the number of vessels carrying AIS, making AIS mandatory for all vessels, or incorporating other ways to track vessels, such as using data from the Canadian Coast Guard (Pizzolato et al., 2014), land-based cameras, or even satellite imagery (Charry et al., 2021). Another potentially useful exercise would be to model the distribution of bowhead whales and vessel traffic in the future under different sea ice/climate change scenarios to determine any forecasted shifts in vessel strike risk for both bowhead populations.

Understanding the scale of vessel strike risk is an important consideration when interpreting our results (see Fig. 3). To put these risk values into context, the highest value for overlap (i.e., bowhead whale density × vessel density before correcting by vessel speed) was 26 for all bowhead datasets. A value of 26 could be achieved in the highest density bowhead whale area (i.e., a normalized bowhead density value of 1) and an average of 26 vessels present in that cell per month. Alternatively, an equivalent overlap value could occur in a cell with even higher vessel density and a lower bowhead whale density (e.g., vessel density = 52, bowhead density = 0.5). Overlap was then corrected by vessel speed, such that the only way that cell values could be equivalent for both overlap and vessel strike risk is if all vessels were traveling at fast speeds (> 20 knots), which is uncommon. Most vessel classes in the Beaufort and Chukchi seas traveled between 5 and 12 knots, based on the interquartile range of measured speeds (Fig. S8). The exception was ferries, which had interquartile ranges reaching >25 knots. For a vessel traveling 10 knots, vessel strike risk is 0.3 times the overlap value. For a vessel traveling 5 knots, vessel strike risk is 0.06 times the overlap. Given that many cells had speeds <10 knots (Figs. S8, S11), the vessel strike risk values would only be a maximum of 0.3 times the overlap value, if not much less than that. The vessel strike risk that we calculated ranged between 0 and 4.70, although only 31 cells across all bowhead datasets had values >1.0.

Although our study focused on the summer shipping season from July through October in North America, West Greenland, and eastern Russia, which is when most of the Arctic has the least sea ice, vessel traffic does occur during other times of the year in other parts of the Arctic, likely resulting in some vessel strike risk for bowhead whales. Three areas with potential for vessel strike risk during November to June include: Hudson Strait and Disko Bay for ECWG, and the Bering Strait and Bering Sea for BCB. Vessels bound for the Port of Churchill in Manitoba or Ragla Mine in Nunavik (Northern Quebec) travel through Hudson Strait much earlier and later into the year than elsewhere in the Canadian Arctic, and overlap with the winter congregation of bowheads in Hudson Strait. West Greenland, and in particular Disko Bay, is another important ECWG congregation area during the winter and spring. The eastern part of Baffin Bay has year-round fishing operations and community resupply traffic (Heide-Jørgensen, pers. obs.). Similarly, BCB whales overwinter in the Bering Sea, where they could potentially encounter fishing vessels (Silber and Adams, 2019), although currently these fisheries tend to operate in the southern Bering Sea far from where bowheads over-winter (Citta et al., 2014, 2012). Ice-strengthened tankers have begun using the Northern Sea Route through Bering Strait and Russian waters during the winter months (Staalesen, 2021), which may lead to increased vessel strike risk for bowhead whales traveling south along the Russian coast in the Chukchi Sea in November and December through the narrow Bering Strait to their core over-winter area in the northern Bering Sea (Citta et al., 2012). More work is needed to fully assess the extent of vessel strike risk to bowhead whales during the winter months and shoulder seasons, especially as the main shipping season expands earlier and later into the year in the increasingly ice-free Arctic.

Alternative methods exist to calculate vessel strike risk. The metrics that we derived do not account for whale behaviour, such as context-dependent avoidance of vessels due to increased underwater noise disturbance (reviewed in Halliday et al., 2020). Additionally, we did not consider the moderating influence of background sound levels on a whale's ability to detect and possibly avoid an approaching vessel.

Furthermore, alternative model formulations for vessel speed, such as the equation by Conn and Silber (2013) would have yielded slightly higher values for vessel strike risk. The model from Kelley et al. (2020) suggests that large vessels traveling <10 knots are still capable of causing lethal strikes due to the force of the impact, although the probability of the vessel strike occurring is reduced because the whale may be able to move away from a slower vessel (Conn and Silber, 2013). Finally, more complex models of vessel strike risk exist that incorporate vessel draft, critical distance, whale velocity, and time in the strike zone (Rockwood et al., 2018). Overall, we provide the first data-based assessment of hypothetical vessel strike risk to bowhead whales using the most comprehensive spatial datasets available. Investigating the sensitivity of vessel strike risk to model assumptions is a logical extension to our analysis.

Another important consideration is that none of the hypothetical vessel strike risk results from our study have been ground-truthed with real-world data on actual vessel strikes. A more direct approach to identify vessel strike risk hotspots would be based on spatial data of vessel strikes and identifying areas with high vessel strikes using similar methodology to how we measured the relative density of bowhead whales, such as kernel densities. Such an analysis would require a long-term dataset of vessel strikes, such as the database used by Laist et al. (2001) for the Atlantic Ocean. Unfortunately, such a dataset does not exist for the Arctic that we are aware of. The remote and often harsh nature of Arctic coastlines makes such data difficult to obtain. However, the lack of data and difficulty collecting data do not preclude action on this issue. Increased focus lately by government agencies on monitoring whale populations and anthropogenic stressors may lead to better availability of vessel strike data for the Arctic in the future. An important recommendation from our study is further effort focused on monitoring whale populations in the Arctic, particularly in these potential hotspots for vessel strikes that we identified.

5. Management implications and conclusions

A number of vessel management measures can be used to reduce vessel strike risk, including slow-downs, avoidance of key areas, implementing protected areas, and restricting vessel traffic to corridors (McWhinnie et al., 2018). These measures have been used on temperate species, such as North Atlantic right whales, to mitigate vessel strike (e.g., Transport Canada, 2018), so there is existing evidence to support efficacy of these mitigation measures. Many of these measures would likely not only benefit bowhead whales, but would also benefit other species that inhabit these areas, such as beluga and narwhal. Although strike risk is likely not as large a threat to small cetaceans, efforts to reduce strike risk will also likely reduce underwater noise and disturbance from vessels, which will benefit beluga and narwhal. Well-placed avoidance areas or vessel corridors can effectively remove all vessel traffic from important areas for bowheads, whereas slowdowns can reduce the risk of lethal strike in certain areas where vessels must transit. These management measures could be effective in areas of increased vessel strike risk, such as those highlighted in this study. Educating mariners about the different bowhead hotspots and implementing marine mammal observers or some form of whale detection technology could further help to reduce vessel strikes.

Two of the hotspots we identified have management measures in place: one for BCB and one for ECWG. There has been a voluntary Notice to Mariners published annually by the Canadian Coast Guard since 2019 requesting that vessels traveling through important bowhead whale and beluga whale habitats in the eastern Beaufort Sea and Amundsen Gulf travel at 10 knots or less (Canadian Coast Guard, 2020). This mitigation measure includes two Marine Protected Areas (Tarium Niryutait and Anguniaqvia Niqiqyuam) and the vessel strike risk hotspot we identified near Tuktoyaktuk.

In the eastern Canadian Arctic, the Ninginganiq National Wildlife Area at Isabella Bay (south of Clyde River, Nunavut) was designated specifically to protect bowhead whales (Environment and Climate Change Canada, 2020). This protected area limits access of vessels to Isabella Bay through a permitting process to minimize interactions between vessels and bowhead whales (Environment and Climate Change Canada, 2020). However, the boundaries of the protected area only cover Isabella Bay and the adjacent ocean 12 nautical miles (~22 km) offshore, whereas the hotspot for increased vessel strike risk that we identified for this area is completely outside the designated boundaries, laying roughly between 5 and 35 km east of the boundary (e.g., Fig. 6). Expanding a 35 km (or even 50 km) buffer around the protected area and designating it as an exclusion area, or creating a corridor for vessels farther offshore, could be an effective way to better protect bowheads in this area.

Two other hotspots for hypothetical vessel strike risk identified by this study are in Cumberland Sound and Gulf of Boothia, and neither have any measures in place to mitigate against vessel strikes. Both are spatially constricted areas where vessel traffic cannot be excluded; therefore, vessel slow-downs might be the most appropriate management measure, especially paired with marine mammal observers actively searching for bowhead whales so they can be avoided.

Finally, within the Alaskan Beaufort, hotspots for vessel strike risk occur in the vicinity of Utqiaġvik and Prudhoe Bay. The United States is currently in the process of designing corridors through the Alaskan Beaufort Sea, which may route vessels farther offshore. If these corridors were mandatory for any vessels transiting through the region (but not those stopping at Utqiaġvik and Prudhoe Bay), it would greatly reduce the overlap between vessels and bowheads in the Alaskan Beaufort Sea.

Vessel strike risk to bowhead whales will likely escalate as vessel traffic continues to increase throughout the Arctic. Identifying hotspots for hypothetical vessel strike risk is an important first step in mitigating this risk. However, continued monitoring and updating is also required to track whether these hotspots are static or dynamic, and, if dynamic, to determine the characteristics of the underlying spatiotemporal variability, which is especially important in the context of climate change-induced shifts in the distribution and composition of prey. Similarly, verifying the hotspots with actual vessel strike data should be a priority. While the overall magnitude of vessel strike risk is likely lower for bowhead whales than it is for non-polar large whale species due to lower vessel traffic in the Arctic, it is crucial to track this threat for bowhead whales, given recent increases in vessel traffic in conjunction with a rapidly changing Arctic environment due to climate change (Meredith et al., 2019). This relatively lower risk also offers a rare opportunity to learn from conservation challenges caused by vessel strikes in temperate locations and apply mitigations strategies that have been shown to be effective for other species before traffic increases more in the Arctic. Bowhead whales are also an important subsistence species for Inuit, underscoring the importance of reducing threats to this species. Proactively managing vessel traffic within the hypothetical strike risk hotspots identified in this study is an important first step towards reducing strike risk to bowhead whales, especially since detecting any increases in vessel strikes will continue to be difficult due to the remote areas occupied by these populations. The hotspots identified in this study also represent smaller areas within the North American Arctic that could be the target of increased monitoring to look for evidence of vessel strikes in both bowhead populations. Reducing and mitigating the impacts of as many human activities as possible on bowhead whales is essential for their conservation and management.

More broadly, our study highlights a relatively simple method to identify potential areas of concern for vessel strikes for large whales, which can be easily replicated in other regions with other species. Researchers do not need to necessarily collect new data on vessels or whales to conduct a vessel strike risk analysis such as we undertook here, since AIS data are becoming more readily available (e.g., from NOAA: https://marinecadastre.gov/ais/) as are animal movement data (e.g., Movebank: https://www.movebank.org/). Our method can allow for a rapid assessment of potential vessel strike risk hotspots, that can be followed-up with more dedicated monitoring and assessment in focused areas which can lead to reduced costs to conservation programs compared to more widespread monitoring.

CRediT authorship contribution statement

William D. Halliday: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Nicole Le Baron:** Methodology, Formal analysis, Investigation, Writing – review & editing, Visualization. **John J. Citta:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Jackie Dawson:** Resources, Data curation, Writing – review & editing. **Thomas Doniol-Valcroze:** Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Megan Ferguson:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Steven H. Ferguson:** Conceptualization, Resources, Data curation, Writing – review & editing, Funding acquisition. **Sarah Fortune:** Methodology, Writing – review & editing. **Lois A. Harwood:** Resources, Data curation, Writing – review & editing. **Mads Peter Heide-Jørgensen:** Resources, Data curation, Writing – review & editing. **Ellen V. Lea:** Resources, Data curation, Writing – review & editing. **Lori Quakenbush:** Resources, Data curation, Writing – review & editing. **Brent G. Young:** Data curation, Writing – review & editing. **David Yurkowski:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Stephen J. Insley:** Resources, Writing – review & editing, Supervision.

Declaration of competing interest

We declare that we have no conflict of interests.

Data availability

Data will be made available on request.

Acknowledgements

BCB telemetry data was collected by the Alaska Department of Fish and Game working with the Alaska Eskimo Whaling Commission, Alaska Native subsistence whalers, the North Slope Borough, Department of Fisheries and Oceans Canada (DFO), and members of the Tuktoyaktuk and Aklavik Hunters and Trappers Committees, with funding from the U. S. Minerals Management Service (now the Bureau of Ocean Energy Management (BOEM)) under contracts M05PC0020, M10PC00085, and M12PC00005, and the U.S. Office of Naval Research under contract N00014-16-1-3019. ECWG tagging was made possible by the Igloolik and Pangnirtung Hunters and Trappers Organizations. Work in Canada was funded by DFO and the Fisheries Joint Management Committee, the Ecosystem Research Initiative (DFO), the Species at Risk Recovery Strategy (DFO) under the *Species at Risk Act*, the Panel for Energy Research and Development, the Nunavut Implementation Fund, the Nunavut Wildlife Management Board, Polar Continental Shelf Program, the Government of Nunavut Fisheries and Sealing, Nunavut Wildlife Research Trust Fund, Nunavut General Monitoring Program, Ocean Tracking Network, and ArcticNet. The ASAMM project, which collected aerial survey data on the BCB population, was funded and co-managed by BOEM and conducted and co-managed by the National Oceanic and Atmospheric Administration. Funding in Greenland for tagging of ECWG bowhead whales was provided by the Commission for Scientific Research in Greenland, the National Ocean Partnership Program, the Danish Cooperation for the Environment in the Arctic, and the Greenland Institute of Natural Resources. This specific vessel strike risk analysis was funded by the Canada Nature Fund for Aquatic Species at Risk (DFO), and DFO separately funded a literature review of vessel strike risk. Satellite AIS data were provided by MEOPAR through an agreement with exactEarth.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109820.

References

Albertsen, C.M., Whoriskey, K., Yurkowski, D., Nielsen, A., Flemming, J.M., 2015. Fast fitting of non-Gaussian state-space models to animal movement data via template model builder. Ecology 96, 2598–2604.

Arctic Council, 2009. Arctic Marine Shipping Assessment 2009 Report.

Ashjian, C.J., Okkonen, S.R., Campbell, R.G., Alatalo, P., 2021. Lingering Chukchi Sea sea ice and Chukchi Sea mean winds influence population age structure of euphausiids (krill) found in the bowhead whale feeding hotspot near Pt. Barrow, Alaska. PLoS One 16, e0254418. https://doi.org/10.1371/journal.pone.0254418.

Barrientos, R., Ascensão, F., D'Amico, M., Grilo, C., Pereira, H.M., 2021. The lost road: do transportation networks imperil wildlife population persistence? Perspect. Ecol. Conserv. https://doi.org/10.1016/j.pecon.2021.07.004.

Bockstoce, J.R., Burns, J.J., 1993. Commercial whaling in the North Pacific sector. In: Burns, John J., Montague, J.J., Cowles, C.J. (Eds.), The Bowhead Whale. Society for Marine Mammalogy, Lawrence, KS, pp. 563–577.

Canadian Coast Guard, 2020. *505 Anguniaqvia niqiqyuam Marine Protected Area (ANMPA) and Tarium Niryutait Marine Protected Areas (TNMPA) – Beluga and Bowhead Whale Protection: Voluntary Avoidance and Slowdown Areas [WWW Document]. Notice to Mariners Publication: Western Edition. https://www.notmar.gc.ca/publications/monthly-mensuel/west-ouest-05-20-en.php#*505ANGUNIAQVIANIQIQYUAMMARINEPROTECTEDAREA(ANMPA)ANDTARIUMNIRYUTAITMARINEPROTECTEDAREAS(TNMPA)-BELUGAANDBOWHEADWHALEPROTECTION:VOLUNTARYAVOIDANCEANDSLOWDOWNAREAS (accessed 8.10.20).

Caughley, G., 1974. Bias in aerial survey. J. Wildl. Manag. 38, 921–933. https://doi.org/10.2307/3800067.

Chambault, P., Albertsen, C.M., Patterson, T.A., Hansen, R.G., Tervo, O., Laidre, K.L., Heide-Jørgensen, M.P., 2018. Sea surface temperature predicts the movements of an Arctic cetacean: the bowhead whale. Sci. Rep. 8, 1–12. https://doi.org/10.1038/s41598-018-27966-1.

Charry, B., Tissier, E., Iacozza, J., Marcoux, M., Watt, C.A., 2021. Mapping Arctic cetaceans from space: a case study for beluga and narwhal. PLoS One 16, e0254380. https://doi.org/10.1371/journal.pone.0254380.

Citta, J.J., Quakenbush, L.T., George, J.C., Heide-Jørgensen, M.P., Brower, H., Adams, B., Brower, L., 2012. Winter movements of bowhead whales (*Balaena mysticetus*) in the Bering Sea. Arctic 65, 13–34.

Citta, J.J., Burns, J.J., Quakenbush, L.T., Vanek, V., George, J.C., Small, R.J., Heide-Jørgensen, M.P., Brower, H., 2014. Potential for bowhead whale entanglement in cod and crab pot gear in the Bering Sea. Mar. Mamm. Sci. 30, 445–459. https://doi.org/10.1111/mms.12047.

Citta, J.J., Quakenbush, L.T., George, J.C., 2021 . Distribution and Behavior of Bering-Chukchi-Beaufort Bowhead Whales as Inferred by Telemetry, 1st ed. Academic Press, The Bowhead Whale.

Clarke, J.T., Brower, A.A., Ferguson, M.C., Willoughby, A.L., Rotrock, A.D., 2020. Distribution and Relative Abundance of Marine Mammals in the Eastern Chukchi Sea, Eastern and Western Beaufort Sea, and Amundsen Gulf, 2019. Annual Report, OCS Study BOEM 2020-027. Seattle. https://repository.library.noaa.gov/view/noaa/24934.

Conn, P.B., Silber, G.K., 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. Ecosphere 4, 43. https://doi.org/10.1890/ES13-00004.1.

Constantine, R., Johnson, M., Riekkola, L., Jervis, S., Kozmian-Ledward, L., Dennis, T., Torres, L.G., Aguilar de Soto, N., 2015. Mitigation of vessel-strike mortality of endangered Bryde's whales in the Hauraki Gulf, New Zealand. Biol. Conserv. 186, 149–157. https://doi.org/10.1016/j.biocon.2015.03.008.

COSEWIC, 2009. COSEWIC Assessment and Update Status Report on the Bowhead Whale Balaena mysticetus, Bering–Chukchi–Beaufort Population and Eastern Canada–West Greenland Population, in Canada.

Davies, K.T.A., Brillant, S.W., 2019. Mass human-caused mortality spurs federal action to protect endangered North Atlantic right whales in Canada. Mar. Policy 104, 157–162. https://doi.org/10.1016/j.marpol.2019.02.019.

Dawson, J., Pizzolato, L., el Howell, S., Copland, L., Johnston, M.E., 2018. Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. Arctic 71, 15–26.

Doniol-Valcroze, T., Gosselin, J.-F., Pike, D., Lawson, J., Asselin, N., Hedges, K., Ferguson, S., 2020a. Distribution and Abundance of the Eastern Canada – West Greenland Bowhead Whale Population Based on the 2013 High Arctic Cetacean Survey, 11. NAMMCO Scientific Publications. https://doi.org/10.7557/3.5315 v+ 27 p.

Doniol-Valcroze, T., Gosselin, J.-F., Pike, D.G., Lawson, J.W., Asselin, N.C., Hedges, K., Ferguson, S.H., 2020b. Narwhal Abundance in the Eastern Canadian High Arctic in 2013, 11. NAMMCO Scientific Publications. https://doi.org/10.7557/3.5100.

Douglas, A.B., Calambokidis, J., Raverty, S., Jeffries, S.J., Lambourn, D.M., Norman, S.A., 2008. Incidence of ship strikes of large whales in Washington state. J. Mar. Biol. Assoc. U. K. 88, 1121–1132. https://doi.org/10.1017/S0025315408000295.

Douglas, D.C., Weinzierl, R., Davidson, S.C., Kays, R., Wikelski, M., Bohrer, G., 2012. Moderating Argos location errors in animal tracking data. Methods Ecol. Evol. 3, 999–1007. https://doi.org/10.1111/j.2041-210X.2012.00245.x.

Duong, T., 2019. ks: Kernel Smoothing. R Package Version 1.11.5.

Environment and Climate Change Canada, 2020. Ninginganiq National Wildlife Area [WWW Document]. https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/locations/ninginganiq.html#toc1 accessed 7.30.21.

Ferguson, S.H., Higdon, J.W., Hall, P.A., Hansen, R.G., Doniol-valcroze, T., 2021. Developing a precautionary management approach for the eastern Canada-West Greenland population of bowhead whales (Balaena mysticetus). Front. Mar. Sci. 8, 709989 https://doi.org/10.3389/fmars.2021.709989.

Ferguson, M.C., Miller, D.L., Clarke, J.T., Brower, A.A., Willoughby, A.L., Rotrock, A.D., 2022. Spatial modeling, parameter uncertainty, and precision of density estimates from line-transect surveys: a case study with Western Arctic bowhead whales. In: Paper SC/68D/ASI/01 presented to the IWC Scientific Committee, May 2022.

Finley, K.J., 1990. Isabella Bay, Baffin Island: an important historical and present-day concentration area for the endangered bowhead whale (*Balaena mysticetus*) of the eastern Canadian Arctic. Arctic 43, 137–152. https://doi.org/10.14430/arctic1604.

Fortune, S.M., Ferguson, S., Trites, A., LeBlanc, B., LeMay, V., Hudson, J., Baumgartner, M., 2020a. Seasonal diving and foraging behaviour of eastern Canada-West Greenland bowhead whales. Mar. Ecol. Prog. Ser. 643, 197–217. https://doi.org/10.3354/meps13356.

Fortune, S.M., Ferguson, S.H., Trites, A.W., Hudson, J.M., Baumgartner, M.F., 2020b. Bowhead whales use two foraging strategies in response to fine - scale differences in zooplankton vertical distribution. Sci. Rep. 10, 20249. https://doi.org/10.1038/s41598-020-76071-9.

Fortune, S.M., Young, B.G., Ferguson, S.H., 2020. Age and sex-specific movement, behaviour and habitat use patterns of bowhead whales in the Eastern Canadian Arctic. In: Polar Biol POBI-D-19. https://doi.org/10.1007/s00300-020-02739-7.

Frasier, T.R., Petersen, S.D., Postma, L., Johnson, L., Heide-Jørgensen, M.P., Ferguson, S. H., 2020. Abundance estimation from genetic mark-recapture data when not all sites are sampled: an example with the bowhead whale. Glob. Ecol. Conserv. 22, e00903 https://doi.org/10.1016/j.gecco.2020.e00903.

George, J.C., Philo, L.M., Hazard, K., Withrow, D., Carroll, G.M., Suydam, R., 1994. Frequency of killer whale (Orcinus orca) attacks and ship collisions based on scarring on bowhead whales (Balaena mysticetus) of the Bering-Chukchi-Beaufort seas stock. Arctic 47, 247–255.

George, J.C., Sheffield, G., Reed, D.J., Tudor, B., Stimmelmayr, R., Person, B.T., Sformo, T., Suydam, R., 2017. Frequency of injuries from line entanglements, killer whales, and ship strikes on Bering-Chukchi-Beaufort seas bowhead whales. Arctic 70, 37–46.

George, J.C., Sheffield, G., Tudor, B.J., Stimmelmayr, R., Moore, M., 2021. Fishing Gear Entanglement and Vessel Collisions. INC, The Bowhead Whale. https://doi.org/10.1016/b978-0-12-818969-6.00036-4.

Givens, G.H., Heide-Jørgensen, M.P., 2021. Abundance. Academic Press, London, UK, The Bowhead Whale. https://doi.org/10.1016/B978-0-12-818969-6.00006-6.

Glista, D.J., DeVault, T.L., DeWoody, J.A., 2009. A review of mitigation measures for reducing wildlife mortality on roadways. Landsc. Urban Plan. https://doi.org/10.1016/j.landurbplan.2008.11.001.

Government of Canada, 2007. Bowhead Whale (Balaena mysticetus), Bering-Chukchi-Beaufort population [WWW Document]. Species at Risk Public Registry. https://species-registry.canada.ca/index-en.html#/species/131-117 (accessed 5.30.22).

Government of Canada, 2016. Arctic offshore oil and gas [WWW Document]. https://www.rcaanc-cirnac.gc.ca/eng/1535571547022/1538586415269 accessed 7.20.21.

Halliday, W.D., Têtu, P.-L., Dawson, J., Insley, S.J., Hilliard, R.C., 2018. Tourist vessel traffic in important whale areas in the western Canadian Arctic: risks and possible management solutions. Mar. Policy 97, 72–81. https://doi.org/10.1016/j.marpol.2018.08.035.

Halliday, W.D., Pine, M.K., Insley, S.J., 2020. Underwater noise and Arctic marine mammals: review and policy recommendations. Environ. Rev. 28, 438–448. https://doi.org/10.1139/er-2019-0033.

Halliday, W.D., Pine, M.K., Citta, J.J., Harwood, L., Hauser, D.D.W., Hilliard, R.C., Lea, E. V., Loseto, L.L., Quakenbush, L., Insley, S.J., 2021. Potential exposure of beluga and bowhead whales to underwater noise from ship traffic in the Beaufort and chukchi seas. Ocean Coast. Manag. 204, 105473.

Harwood, L.A., Lea, E.V., Raverty, S.A., Hall, P.A., Linn, E., Postma, L., Nielsen, O., 2017a. Observations of beachcast bowhead whales (Balaena mysticetus) in the southeastern Beaufort Sea and Amundsen gulf, 1987–2016. Can. FieldNat. 131, 270–279. https://doi.org/10.22621/cfn.v131i3.2028.

Harwood, L.A., Quakenbush, L.T., Small, R.J., George, J.C., Pokiak, J., Pokiak, C., Heide-jørgensen, M.P., Lea, E.V., Brower, H., 2017b. Movements and inferred foraging by bowhead whales in the Canadian Beaufort Sea during august and September, 2006–12. Arctic 70, 161–176. https://doi.org/10.14430/arctic4648.

International Maritime Organization, 2014. International Convention for the Safety of Life at Sea (SOLAS).

Johnson, D., London, J., 2018. crawl: An R Package for Fitting Continuous-time Correlated Random Walk Models to Animal Movement Data. https://doi.org/10.5281/zenodo.596464.

Johnson, D.S., London, J.M., Lea, M., Durban, J.W., 2008. Continuous-time correlated random walk model for animal telemetry data. Ecology 89, 1208–1215.

Kelley, D.E., Vlasic, J.P., Brillant, S.W., 2020. Assessing the lethality of ship strikes on whales using simple biophysical models. Mar. Mamm. Sci. 1–17 https://doi.org/10.1111/mms.12745.

Koski, W.R., Miller, G.W., Davis, R.A., 1988. The potential effects of tanker traffic on the bowhead whale in the Beaufort Sea. Environ. Stud. 58 https://doi.org/10.1017/CBO9781107415324.004.

Laist, David W., Knowlton, Amy R., Mead, James G., Collet, Anne S., Podestà, M., 2001. Collisions between ships and whales. Mar. Mamm. Sci. 17, 35–75. https://doi.org/10.1111/j.1748-7692.2001.tb00980.x.

Li, X., Stephenson, S.R., Lynch, A.H., Goldstein, M.A., Bailey, D.A., Veland, S., 2021. Arctic shipping guidance from the CMIP6 ensemble on operational and infrastructural timescales. Clim. Chang. 167, 23. https://doi.org/10.1007/s10584-021-03172-3.

Matthews, C.J.D., Breed, G.A., LeBlanc, B., Ferguson, S.H., 2020. Killer whale presence drives bowhead whale selection for sea ice in Arctic seascapes of fear. Proc. Natl. Acad. Sci. U. S. A. 117, 6590–6598. https://doi.org/10.1073/pnas.1911761117.

McWhinnie, L.H., Halliday, W.D., Insley, S.J., Hilliard, C., Canessa, R.R., 2018. Vessel traffic in the Canadian Arctic: management solutions for minimizing impacts on whales in a changing northern region. Ocean Coast. Manag. 160, 1–17. https://doi.org/10.1016/j.ocecoaman.2018.03.042.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C., Ottersen, G., Pritchard, H., Schuur, E.A.G., 2019. Polar regions. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, J., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Meyer-Gutbrod, E.L., Greene, C.H., 2018. Uncertain recovery of the North Atlantic right whale in a changing ocean. Glob. Chang. Biol. 24, 455–464. https://doi.org/10.1111/gcb.13929.

Moore, M.J., 2014. How we all kill whales. ICES J. Mar. Sci. 71, 760–763. https://doi.org/10.1093/icesjms/fsu008.

Moore, M.J., Rowles, T.K., Fauquier, D.A., Baker, J.D., Biedron, I., Durban, J.W., Hamilton, P.K., Henry, A.G., Knowlton, A.R., McLellan, W.A., Miller, C.A., Pace, R. M., Pettis, H.M., Raverty, S., Rolland, R.M., Schick, R.S., Sharp, S.M., Smith, C.R., Thomas, L., Ziccardi, M.H., van der Hoop, J.M., 2021. Assessing North Atlantic right whale health: threats, and development of tools critical for conservation of the species. Dis. Aquat. Organ. 143, 205–226. https://doi.org/10.3354/dao03578.

Mudryk, L.R., Dawson, J., Howell, S.E.L., Derksen, C., Zagon, T.A., Brady, M., 2021. Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. Nat. Clim. Chang. https://doi.org/10.1038/s41558-021-01087-6.

NOAA, 2022. Bowhead Whale. https://www.fisheries.noaa.gov/species/bowhead-whale#:~:text=Population%20Status&text=The%20United%20States%20listed%20all,the%20Marine%20Mammal%20Protection%20Act (accessed 5.22.22).

O'Toole, M., Queiroz, N., Humphries, N.E., Sims, D.W., Sequeira, A.M.M., 2021. Quantifying effects of tracking data bias on species distribution models. Methods Ecol. Evol. 12, 170–181. https://doi.org/10.1111/2041-210X.13507.

Olnes, J., Citta, J.J., George, J.C., Harwood, L.A., Lea, E.V., Heide-Jørgensen, M.P., 2020. Use of the Alaskan Beaufort Sea by bowhead whales (*Balaena mysticetus*) tagged with satellite transmitters, 2006–18. Arctic 73, 278–291. https://doi.org/10.14430/arctic70865.

Pagany, R., 2020. Wildlife-vehicle collisions - influencing factors, data collection and research methods. Biol. Conserv. https://doi.org/10.1016/j.biocon.2020.108758.

PAME, 2020. The Increase in Arctic Shipping: 2013-2019.

PAME, 2021. Shipping in the Northwest Passage: Comparing 2013 With 2019.

Parks, S.E., Warren, J.D., Stamieszkin, K., Mayo, C.A., Wiley, D., 2012. Dangerous dining: surface foraging of North Atlantic right whales increases risk of vessel collisions. Biol. Lett. 8, 57–60. https://doi.org/10.1098/rsbl.2011.0578.

Pizzolato, L., Howell, S.E.L., Derksen, C., Dawson, J., Copland, L., 2014. Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Clim. Chang. 123, 161–173. https://doi.org/10.1007/s10584-013-1038-3.

Quakenbush, L.T., Citta, J.J., 2019. Satellite tracking of bowhead whales: habitat use, passive acoustics and environmental monitoring, Final Report. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Alaska Outer Continental Shelf Region, Anchorage, AK. OCS Study BOEM 2019-076. https://www.boem.gov/sites/default/files/documents/regions/alaska-ocs-region/environment/BOEM%202019-076.pdf.

Quakenbush, L.T., Citta, J.J., George, J.C., Small, R.J., Heide-Jørgensen, M.P., 2010. Fall and winter movements of bowhead whales (Balaena mysticetus) in the Chukchi Sea and within a potential petroleum development area. Arctic 63, 289–307.

Rockwood, R.C., Calambokidis, J., Jahncke, J., 2018. High mortality of blue, humpback and fin whales from modeling of vessel collisions on the U.S. West Coast suggests population impacts and insufficient protection. PLoS One 12, e0183052. https://doi.org/10.1371/journal.pone.0183052.

Schoeman, R.P., Patterson-Abrolat, C., Plön, S., 2020. A global review of vessel collisions with marine animals. Front. Mar. Sci. 7, 292. https://doi.org/10.3389/fmars.2020.00292.

Silber, G.K., Adams, J.D., 2019. Vessel operations in the Arctic, 2015–2017. Front. Mar. Sci. 6, 573. https://doi.org/10.3389/fmars.2019.00573.

Silber, G.K., Slutsky, J., Bettridge, S., 2010. Hydrodynamics of a ship/whale collision. J. Exp. Mar. Biol. Ecol. 391, 10–19. https://doi.org/10.1016/j.jembe.2010.05.013.

Simard, Y., Roy, N., Giard, S., Aulanier, F., 2019. North Atlantic right whale shift to the Gulf of St. Lawrence in 2015, revealed by long-term passive acoustics. Endanger. Species Res. 40, 271–284. https://doi.org/10.3354/esr01005.

Smith, L.C., Stephenson, S.R., 2013. New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences 110, E1191–E1195. https://doi.org/10.1073/pnas.1214212110.

Staalesen, A., 2021. Tanker embarks on first ever mid-winter voyage on Northern Sea Route [WWW Document]. The Barents Observer. https://thebarentsobserver.

com/en/arctic-lng/2021/02/tanker-embarks-first-ever-mid-winter-voyage-northern-sea-route (accessed 10.29.21).

Stafford, K.M., 2019. Increasing detections of killer whales (Orcinus orca), in the Pacific Arctic. Mar. Mamm. Sci. 35, 696–706. https://doi.org/10.1111/mms.12551.

Stephenson, S.R., Smith, L.C., Agnew, J.A., 2011. Divergent long-term trajectories of human access to the Arctic. Nat. Clim. Chang. 1, 156–160. https://doi.org/10.1038/nclimate1120.

Suydam, R., George, J.C., 2021. Current Indigenous Whaling. The Bowhead Whale. INC. https://doi.org/10.1016/b978-0-12-818969-6.00032-7.

Thewissen, J.G.M., George, J.C., 2021. Commercial Whaling. Academic Press, London, The Bowhead Whale. https://doi.org/10.1016/b978-0-12-818969-6.00033-9.

Transport Canada, 2018. Protecting North Atlantic right whales from ship strikes in the Gulf of St. Lawrence. https://www.tc.gc.ca/en/services/marine/navigation-marine-conditions/protecting-north-atlantic-right-whales-ship-strikes-gulf-st-lawrence.html (accessed 6.21.18).

Vanderlaan, A.S.M., Taggart, C.T., 2007. Vessel collisions with whales: the probability of lethal injury based on vessel speed. Mar. Mamm. Sci. 23, 144–156. https://doi.org/10.1111/j.1748-7692.2006.00098.x.

Vanderlaan, A.S.M., Taggart, C.T., 2009. Efficacy of a voluntary area to be avoided to reduce risk of lethal vessel strikes to endangered whales. Conserv. Biol. 23, 1467–1474. https://doi.org/10.1111/j.1523-1739.2009.01329.x.

Wartzok, D., Watkins, W.A., Wursig, B., Malme, C.I., 1989. Movements and behaviors of bowhead whales in response to repeated exposures to noises associated with industrial activities in the Beaufort Sea. Unpublished report. In: Available at Amoco Production Company, 1670 Broadway, Denver, CO 80202.

Willoughby, A.L., Stimmelmayr, R., Brower, A.B., Clarke, J.T., Ferguson, M.C., 2020. Bowhead Whale Carcasses in the Eastern Chukchi and Western Beaufort Seas. International Whaling Commission Report SC/68B/ASW/02Rev1.

Wood, S.N., 2017. Generalized additive models: an introduction with R. Chapman and Hall/CRC.

Yurkowski, D.J., Auger-Méthé, M., Mallory, M.L., Wong, S.N.P., Gilchrist, G., Derocher, A.E., Richardson, E., Lunn, N.J., Hussey, N.E., Marcoux, M., Togunov, R. R., Fisk, A.T., Harwood, L.A., Dietz, R., Rosing-Asvid, A., Born, E.W., Mosbech, A., Fort, J., Grémillet, D., Loseto, L., Richard, P.R., Iacozza, J., Jean-Gagnon, F., Brown, T.M., Westdal, K.H., Orr, J., LeBlanc, B., Hedges, K.J., Treble, M.A., Kessel, S. T., Blanchfield, P.J., Davis, S., Maftei, M., Spencer, N., McFarlane-Tranquilla, L., Montevecchi, W.A., Bartzen, B., Dickson, L., Anderson, C., Ferguson, S.H., 2019. Abundance and species diversity hotspots of tracked marine predators across the North American Arctic. Divers. Distrib. 25, 328–345. https://doi.org/10.1111/ddi.12860.