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Vessel risks to marine wildlife in the Tallurutiup Imanga National Marine Conservation Area and the eastern entrance to the Northwest Passage

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ABSTRACT

The Arctic is changing rapidly due to climate change, which is allowing unprecedented levels of vessel traffic to transit the region. Vessel traffic can negatively affect marine wildlife in a number of ways, particularly in areas where vessels overlap with high concentrations of ecologically important species, and the significance of these impacts are of increased concern when the wildlife are also culturally important. Tallurutiup Imanga National Marine Conservation Area, located in Lancaster Sound, Nunavut, Canada, at the eastern entrance to the Northwest Passage, is experiencing the greatest levels of vessel traffic in the Canadian Arctic, and is important habitat for marine wildlife, including marine mammals and seabirds. Here, we examined the overlap between vessel traffic, including modeled underwater noise levels, and the distribution of two cetacean species, beluga and narwhal, and three seabird species, thick-billed murre, northern fulmar, and black-legged kittiwake. Narwhal had the highest vessel risk in Eclipse Sound and Milne Inlet, all three seabirds had high vessel risk at the eastern entrance to Eclipse Sound, with additional areas for northern fulmar at southern Devon Island and for black-legged kittiwake at Prince Leopold Island, and belugas had the highest vessel risk along southern and eastern Devon Island. Our results provide crucial information for implementing monitoring, conservation, and management initiatives for species inhabiting this protected area, and allow for a better understanding of the potential cultural implications of vessel-based marine wildlife impacts that will affect traditional subsistence hunting and local livelihoods.

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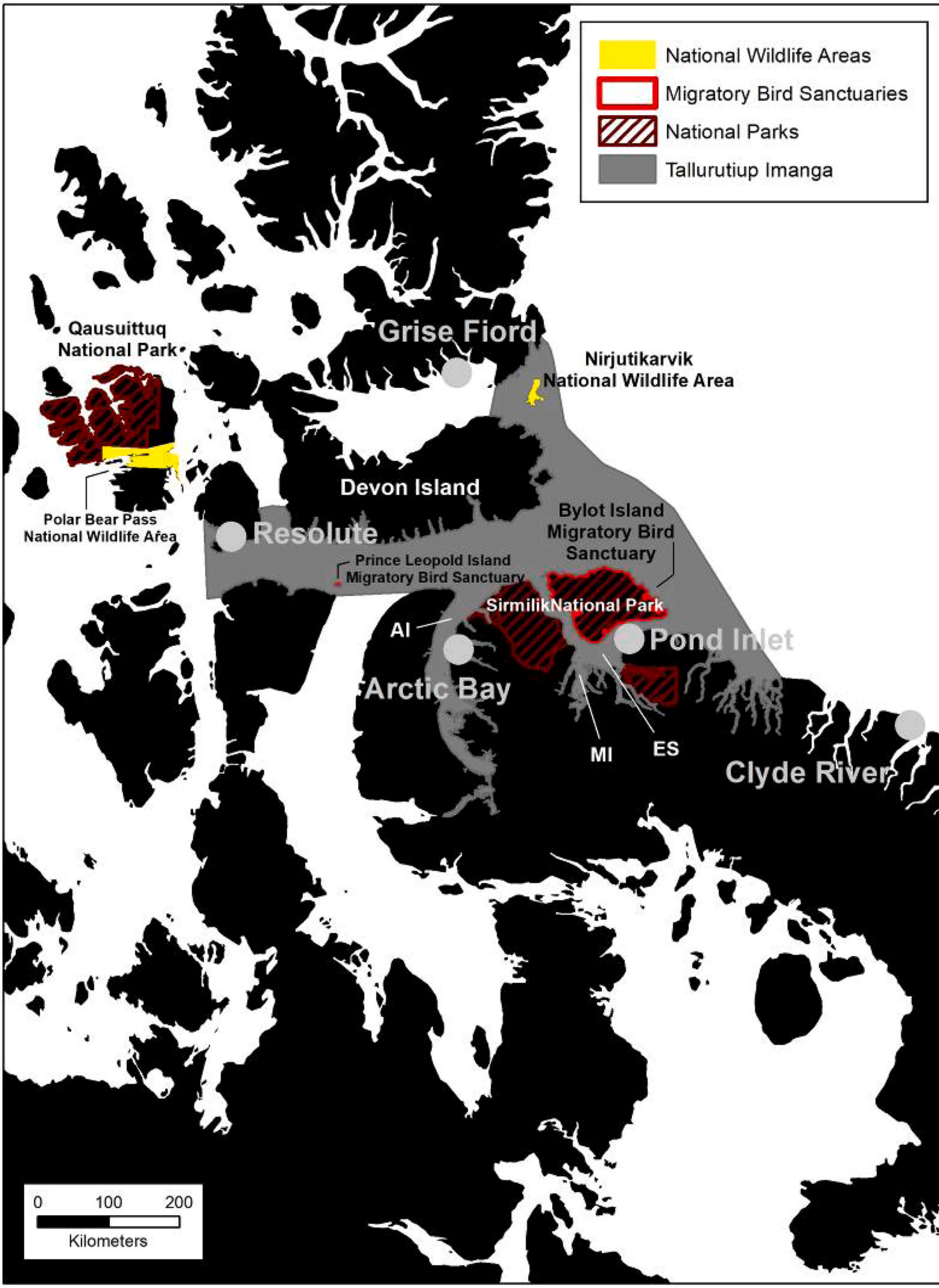

Fig. 1. Map of the study area highlighting Tallurutiup Imanga (Lancaster Sound) National Marine Conservation Area (in grey), other protected areas, and nearby communities. AI: Admiralty Inlet, ES: Eclipse Sound, MI: Milne Inlet.

1. Introduction

Changes to the Arctic environment as a result of climate change are happening at a faster rate than most other places on Earth (Bush et al., 2019; IPCC, 2013, 2019). Over the past 25 years vessel traffic in Arctic Canada has more than tripled (Dawson et al., 2018) and future growth is expected as a result of climate change-induced increases in the spatial and temporal extent of open water areas, as well as trends related to global trade, resource development, and tourism (Dawson et al., 2018; Pizzolato et al., 2016; Smith and Stephenson, 2013). The impacts of increased vessel traffic will not be uniform across the Arctic, but rather will be concentrated in areas where high traffic density overlaps with areas of high ecological and cultural significance (Dawson et al., 2020; Halliday et al., 2021).

One region of particular significance is the Northwest Passage (NWP) in Arctic Canada, which forms a ~4000 km, east-west northern linkage between the Atlantic and Pacific oceans and which provides essential habitat for biologically and culturally important wildlife species. Vessels using this route can travel thousands of kilometers less than using the Panama Canal or Suez Canals to transport materials from Europe to Asia, depending on the port locations, representing a substantial time and cost savings for international shipping (Khon et al., 2010; Lu et al., 2014). The route also supports fundamental community re-supply, access to regional resource development operations, and has become a popular cruise tourism itinerary (Copland et al., 2021; Dawson et al., 2018). However, use of this route is fraught with contentious issues regarding the international status of the waters and Canadian sovereignty (Byers and Lalonde, 2009; Steinberg, 2014), Indigenous rights and concerns (Cameron, 2012; Stewart et al., 2013), environmental concerns (Dawson et al., 2014), and international security (Huebert, 2011). Nonetheless, as sea ice conditions continue to ameliorate for vessel traffic through the NWP routes and as vessel traffic increases in Arctic waters (Dawson et al., 2018), industrial, commercial and international government attention will increase on this waterway.

The NWP has, by far, experienced the greatest increase in vessel traffic in the Canadian Arctic over the past decade (Dawson et al., 2018), and the eastern entrance to the NWP was identified for federal protection because of its high ecological and cultural significance (Parks Canada, 2021). Millions of seabirds and sea ducks use these waters, which provide critical foraging habitat during the breeding season and are also used by non-breeding seabirds (Gaston et al., 2012; Mallory et al., 2019; Wong et al., 2014). This area also provides important habitat, including calf-rearing habitat, and a migration pathway for endemic Arctic marine mammal species (Yurkowski et al., 2019), such as narwhal (*Monodon monoceros*), ringed seals (*Pusa hispida*) and polar bears (*Ursus maritimus*). Increased vessel traffic leaves marine wildlife vulnerable to many threats including: exclusion from important foraging/offspring rearing areas due to disturbance from vessels or underwater noise, increased risk of oiling events (both chronic and catastrophic) and risk of collision with vessels (Burek et al., 2008; Halliday et al., 2020a; Redfern et al., 2013; Schwemmer et al., 2011; Shannon et al., 2016; Weise and Roberston, 2004). Vessel-induced adjustments to local wildlife populations or habitat use can have a significant, deleterious effect on local Indigenous (Inuit) communities, because local inhabitants still rely heavily on harvest of wild foods as the key part of their diet (Ford, 2009; Kinloch et al., 1992).

In recent years Canada has been working to improve marine protection for key ocean habitats, consistent with a general global recognition of degradation of our oceans and a need for marine spatial planning and conservation (Agardy et al., 2011; Asaad et al., 2017) pursuant to the Aichi Targets of the UN Convention on Biological Diversity (https://www.cbd.int/sp/targets/; see also Sala et al., 2018). Important marine habitat sites for Arctic biota (e.g., Mallory et al., 2019; Yurkowski et al., 2019) as well as locations of high historic or cultural relevance are being identified, in part due to concerns over changes induced by global warming (Hollesen et al., 2018), and slowly some of these sites are acquiring legislated protection. A particularly successful effort has been achieved for the Lancaster Sound National Marine Conservation Area (NMCA), known as Tallurutiup Imanga (TI) NMCA (Parks Canada, 2021).

The Canadian federal government (Parks Canada) and the relevant Regional Inuit Associations (RIA) (i.e. Kitikmeot Inuit Association (KIA) and Qikiqtani Inuit Association (QIA)) are working toward the development of a management plan for the proposed TI NMCA. While considerable data exist on the ecological and cultural heritage importance of this area (Parks Canada, 2021), a lack of data and research on vessel related impacts in the Arctic is challenging the establishment of evidence-based plans for understanding and mitigating vessel risks to these values.

In this study, we compiled existing marine mammal aerial survey and satellite telemetry data and at-sea seabird survey data within the TI NMCA to create a unique and unprecedented dataset to examine the implications and risk of increased vessel traffic on a diversity of valued resources to inform management and conservation decisions. This study builds on Kochanowicz et al. (2021), who examined the overlap between modeled vessel noise and hotspots for cetaceans identified by both telemetry and Inuit knowledge in TI NMCA. Specifically, this study incorporates seabird data and additional cetacean data, uses a more spatially-explicit approach, and includes a direct analysis of the overlap between areas of vessel traffic and marine wildlife. The objectives of the study were to:

1) Evaluate vessel traffic trends (1990–2018) in TI NMCA in terms of overall traffic and by vessel type;
2) Model vessel noise in TI NMCA to identify hotspots of vessel noise;
3) Examine the distribution and density of key marine wildlife to Inuit culture and Arctic ecosystems, specifically seabirds and marine mammals during the same season as vessel traffic (July to October; henceforth referred to as the shipping season);
4) Examine the overlap between vessel traffic and modeled underwater vessel noise and the distribution and density of marine wildlife within the TI NMCA to identify areas of heightened risk.

The results from this study will be an important resource for the management of TI NMCA, particularly related to reducing the risk of vessel impacts on marine wildlife.

2. Methods

2.1. Study area

The study area was in Nunavut at the eastern entrance to the Northwest Passage, the fabled navigable water route between the Atlantic and Pacific oceans across the top of North America. This entire region is in the process of becoming a Canadian National Marine Conservation Area (NMCA), named *Tallurutiup Imanga* in Inuktitut (Lancaster Sound). NMCAs are coastal land and water areas that Parks Canada manages for ecologically sustainable use (Parks Canada, 2021). The area is ecologically sensitive and culturally significant because of the specific habitat it offers to various marine mammal species such as polar bears, ringed seals, bearded seals (*Erignathus barbatus*), beluga whales (*Delphinapterus leucas*), bowhead whales (*Balaena mysticetus*) and narwhals (Parks Canada, 2021). Furthermore, it is a critical region for supporting many of the largest seabird colonies in the Canadian high Arctic for thick-billed murre (*Uria lomvia*), northern fulmar (*Fulmarus glacialis*) and black-legged kittiwake (*Rissa tridactyla*), as well as providing key migration staging and foraging habitat for sea ducks and endangered species such as the iconic ivory gull (*Pagophila eburnea*; Mallory et al., 2019). There are five communities in and around Tallurutiup Imanga: Arctic Bay (Ikpiarjuk in Inuktitut; population 1752), Clyde River (Kangiqtugaapik; 2254), Grise Fiord (Aujuittuq; 319), Pond Inlet (Mittimatalik; 3326) and Resolute Bay (Qausuittuq; 420; Fig. 1)

Table 1
Marine wildlife datasets used in this study.

Dataset	Years	Months	Sample Size[a]	Geographic Focus
Beluga Whale Satellite Telemetry	1995–1996	July-October	27	Tagged near Somerset Island. Tagged belugas moved throughout western and northeastern TI NMCA.
Narwhal Satellite Telemetry	1997–1999 2003–2005 2009–2012 2016–2018	July-October	99	Tagged near Somerset Island, Admiralty Inlet, and Eclipse Sound. Tagged narwhal moved throughout TI NMCA.
Bowhead Whale Satellite Telemetry	2003–2017	July-October	17	Tagged in Admiralty Inlet, Foxe Basin, and Cumberland Sound. Tagged bowheads moved mostly in Admiralty Inlet and towards Prince Regent Inlet.
Ringed Seal Satellite Telemetry	2012–2013 2017–2018	July-October	12	Tagged near Resolute Bay and Eclipse Sound. Tagged ringed seals moved throughout TI NMCA.
Narwhal Aerial Survey	2013, 2016	August	3830 km^2	Within the TI NMCA, the 2013 surveys were flown mostly in Admiralty Inlet and Eclipse Sound while the 2016 survey only included Eclipse Sound.
Seabird Surveys	2007–2018	July-October	1490 km^2	Surveys were conducted throughout TI NMCA.

[a] Sample size refers to the number of tagged individuals for telemetry and the area surveyed for narwhal aerial surveys and seabird surveys.

(Nunavut Planning Commission, 2021).

2.2. Marine wildlife datasets

2.2.1. Aerial surveys

Aerial surveys were designed to cover the range of six summering stocks of narwhal in Canada's high-Arctic that included the TI NMCA in August 2013 (Doniol-Valcroze et al., 2020) and one summering stock (Eclipse Sound) in August 2016 (Marcoux et al., 2019) (Table 1). All summering stocks are part of the Baffin Bay population of narwhal. In short, aerial surveys were flown using a de Havilland Twin Otter (DH-6) at a target ground speed of 185 km/h (100 knots) and a target altitude of 305 m (1000 ft) for visual survey (double platform observer-based experiment) in 2013 and at 610 m (2000 ft) for the photographic survey in 2016. The double-platform visual aerial survey was composed of three teams of four observers, with each observer sitting at a bubble window for visual observations. For the photographic aerial survey, a Nikon D800 camera with a 25 mm lens and connected to a GPS unit was equipped to the ventral camera port at the rear of the aircraft and mounted straight down. Photographs were taken every 7 s resulting in 875.4 × 585.2 m ground area covered by each photograph and 20% overlap between consecutive photographs. Details of the two survey can be found in Doniol-Valcroze et al. (2020) and Marcoux et al. (2019). Although all cetacean species were counted during the aerial surveys, we focus on narwhal given that the survey locations were targeted specifically for narwhal.

2.2.2. Satellite telemetry

We used existing telemetry data from marine mammal species commonly observed within the TI NMCA including beluga whales from the Eastern High Arctic-Baffin Bay population (1995–1996; 27 individuals), narwhal from the Baffin Bay population (1997–2017; 99 individuals), bowhead whales from the Eastern Canada-West Greenland population (2003–2017; 17 individuals) and ringed seals from the Arctic population (2012–2018; 12 individuals) (Table 1). Only telemetry data from the months of July to October were included in subsequent analysis to correspond with the shipping season. Details on capture and instrumentation are detailed in Richard et al. (2001), Dietz et al. (2008), Ferguson et al. (2010), Yurkowski et al. (2016), and Shuert et al. (2021). An ARGOS geolocation system was used on all satellite-relay data-loggers, which were programmed to transmit at least one location per day. Due to the high spatial error of ARGOS data (0.3–36 km; Costa et al., 2010), we used a discrete-time correlated random walk in the form of hierarchical state-space models (Jonsen, 2016; Jonsen et al., 2005) to reduce location error and standardize location estimates per individual to one location per day. A detailed description of the methods can be found in Yurkowski et al. (2019).

2.2.3. At-sea surveys

We used at-sea seabird survey data (2007–2018) from the Eastern Canada Seabirds at Sea (ECSAS) database, maintained by the Canadian Wildlife Service (Canadian Wildlife Service, Environment and Climate Change Canada, 2021) (Table 1). Only data collected between July and October were used to correspond with the shipping season. Surveys were conducted using a standardized protocol (Gjerdrum et al., 2012) from vessels of opportunity by trained and experienced observers. A single observer scanned a 90° angle from the port or starboard side, usually from the bridge. For each consecutive, five- minute observation period, the observer recorded species (or guild), flock size, and behavior (flying or on the water) within a 300 m strip-width transect. All birds on the water within the 300 m strip were recorded. To avoid over-estimating flying birds that move faster than the vessel (Tasker et al., 1984), a "snapshot" method was used: flying birds within 300 m of the observer were recorded every 300 m traveled. Species counts for each observation period were not adjusted for the fact that detectability of birds decreases with increasing distance from the observer. However, results still reflect relative high and low use areas.

2.2.4. Marine wildlife analysis

All data were projected to a Lambert azimuthal equal-area projection before analysis. Spatial density maps were developed within the TI NMCA for each marine mammal and seabird species by summing the unique number of sightings for each species from the survey data within 10 × 10 km grid cells (hereafter referred to as 10 km cells). For seabirds, we corrected for survey effort by dividing densities by number of km^2 surveyed within each grid cell. For narwhals, we accounted for aerial survey effort by combining 2013 and 2016 transects and dividing the total number of individuals by km surveyed per grid cell (see Fig. 3). We constructed spatial density maps for beluga, narwhal, bowhead, and ringed seals from satellite telemetry data by summing the number of unique individuals for each species within 10 km cells. Satellite telemetry and aerial survey data for narwhals were analyzed separately. Effort-corrected densities were then used in subsequent analyses regarding risk to marine mammals and seabirds via vessel traffic intensity and associated noise footprints.

2.3. Vessel data

2.3.1. Vessel traffic analysis

Two datasets were used for analyses of vessel traffic. First, a long-term dataset (1990–2016) was compiled from vessel reporting data from the Canadian Coast Guard for vessels traveling through the NORDREG zone to examine historical trends in vessel traffic. The methods for creating this dataset are fully described elsewhere (Dawson et al., 2018; Pizzolato et al., 2014, 2016), but briefly, individual vessel reporting locations were converted into vessel tracks using a least cost path approach, and then the total distance traveled by all vessels within a

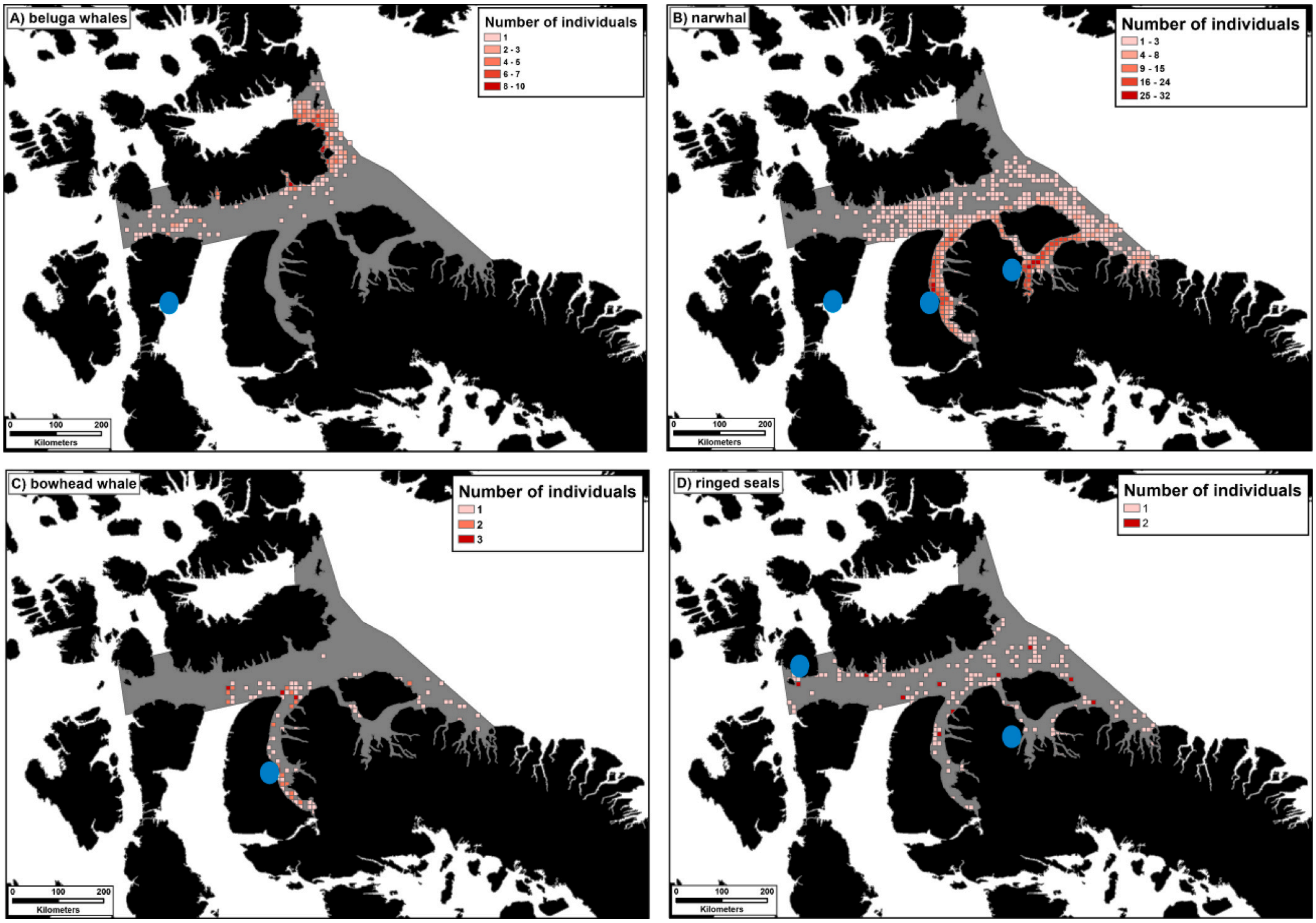

Fig. 2. Spatial distributions of unique number of tracked individuals of beluga whales (A), narwhal (B), bowhead whales (C) and ringed seals (D) in the Tallurutiup Imanga National Marine Conservation Area during the shipping season from 19 July to 10 October at a 10 × 10 km spatial resolution. Blue dots represent the tagging locations for a species. Cells with no data within the study area are grey.

year was calculated in 10 km grid cells. Trends in vessel traffic through time were then examined within the TI NMCA. The period of 1990–2000 was used as a baseline for comparison, and then three different phases of vessel traffic were compared to this baseline: Phase 1 (2001–2005), Phase 2 (2006–2010), and Phase 3 (2011–2016).

The second vessel traffic dataset was based on satellite Automatic Identification System (AIS) data (exactEarth, Cambridge, ON), and was used to examine current (2015–2018) trends in vessel traffic and to model underwater noise levels, both of which were then used for the risk analysis (see Risk Analysis section). Raw AIS points were connected into tracks for individual vessels. The distance traveled by all vessels within a year was then calculated in 10 km grid cells throughout the TI NMCA, and then averaged across years.

2.3.2. Vessel noise modeling

The methods used for vessel noise modeling are the same as those used in Halliday et al. (2021) and Kochanowicz et al. (2021), and the detailed methods are provided in the Appendix. Briefly, frequency-dependent propagation loss was modeled throughout the TI NMCA using the software dBSea 2.0 (Irwin Carr Consulting, Northern Ireland) for four different vessel classes (bulk carriers, cruise ships, government research vessels/ice breakers, and tug boats) to account for coarse differences in how sound propagates away from vessels. Received levels in 500 × 500 m grid cells were calculated for individual vessels (from satellite AIS data) along their entire track out to a radius of 10 km away throughout the TI NMCA, accounting for the average source level for the vessel class and different zones of propagation loss in the region. Received levels were then converted into a binary raster denoting whether received levels exceeded the 120 dB re 1 μPa noise disturbance threshold for marine mammals (National Marine Fisheries Service, 2016; Southall et al., 2007). An underwater noise disturbance threshold has not been established for seabirds; therefore, a value of 120 dB was used to align with marine mammal results. This binary raster was then summed across all vessels within each year. The final output is equivalent to the number of times that each 500 m grid cell exceeds the 120 dB noise disturbance threshold within the shipping season. Outputs for each year between 2015 and 2018 were then averaged, and converted to a 10 km grid cell to match the same spatial resolution of all other datasets used in the Risk Analysis (see next section). The 10 km output represents the average number of times that the 500 m cells within each 10 km cell exceed the 120 dB noise disturbance threshold.

2.4. Risk analysis

Vessel traffic intensity was calculated as average total distance traveled by vessels (based on satellite AIS data) within a year between 2015 and 2018 in the TI NMCA per 10 km grid cell (see Vessel Data above). Grid cells with higher values represent higher potential for marine wildlife to interact with vessels during the shipping season. To determine vessel overlap risk with marine wildlife, we then multiplied marine mammal and seabird species density by vessel traffic intensity for each species. We then normalized the outputs between 0 and 1 by dividing the output by the maximum possible risk value for each species separately. Across all species, a value of one represents the highest

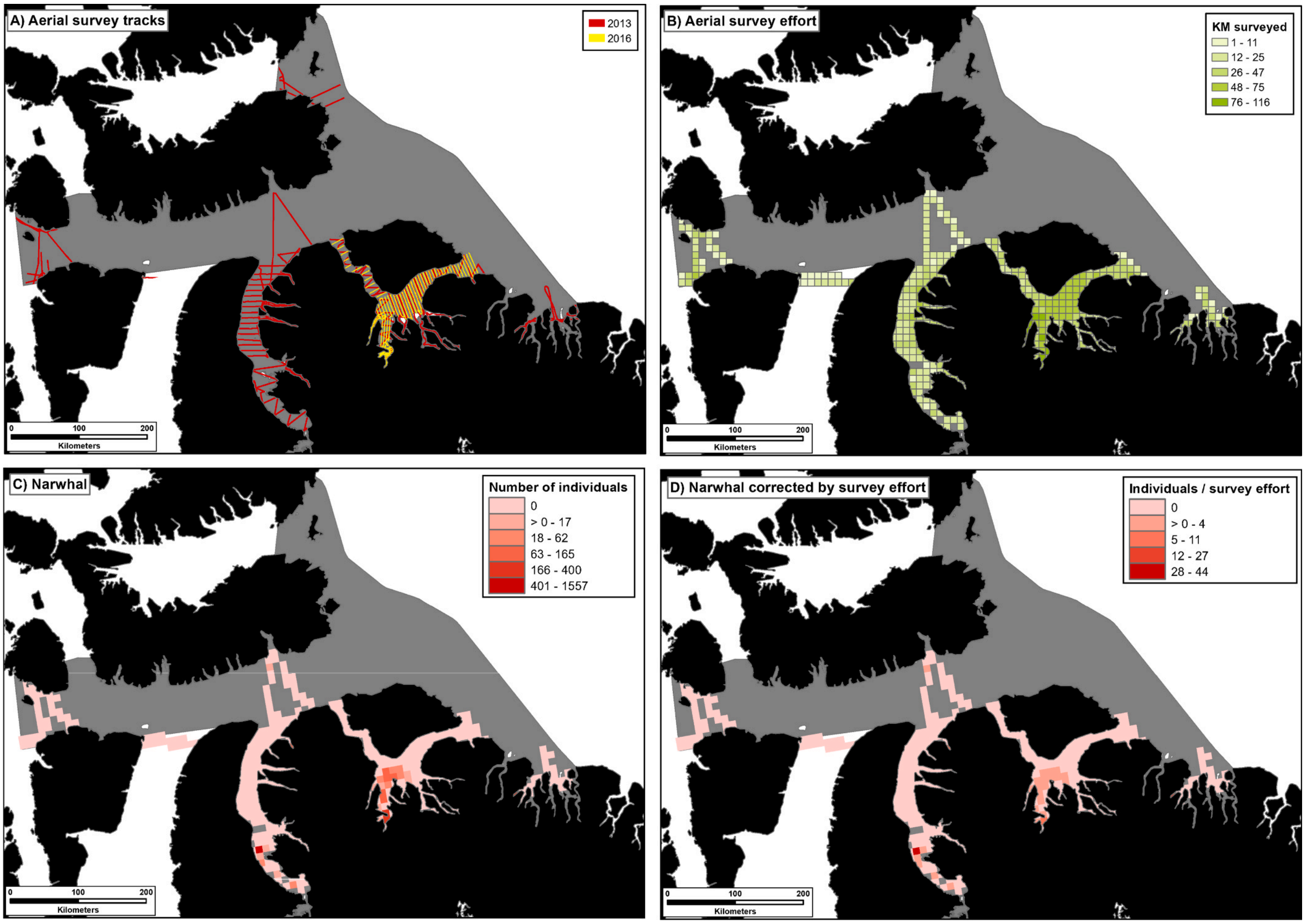

Fig. 3. Narwhal aerial survey tracks in 2013 and 2016 in the Tallurutiup Imanga National Marine Conservation Area (TI NMCA) (A). Narwhal aerial survey tracks corrected for survey effort (total km surveyed within each 10 × 10 km grid cell) (B). Spatial distribution of the number of narwhal observed per 10 × 10 km grid cell within the TI NMCA (C). Narwhal abundance per 10 × 10 km grid cell corrected by survey effort (number of individuals divided by km surveyed) (D). Cells with no data within the study area are grey.

possible risk for that species (i.e. a grid cell where the highest animal density overlapped with high vessel intensity), and zero represents areas where either no vessels traveled or where no individuals of a species were observed. We used the same approach to calculate vessel noise risk per species, using the modeled noise output from Section 2.3.2.

3. Results

3.1. Marine mammals in TI NMCA

The number of observed marine mammals per 10 km grid cell ranged from 0 to 1557 (44 individuals / km^2 when corrected for aerial survey effort; Figs. 2 and 3). Marine mammals were distributed throughout the TI NMCA during summer and fall with highest densities of beluga occurring along the southern and eastern shores of Devon Island (Fig. 2), and highest numbers of narwhal via both aerial survey and satellite telemetry data within Eclipse Sound, Milne Inlet and Admiralty Inlet (Figs. 2 and 3). Bowhead whales and ringed seals only occurred in a few cells, with bowhead whales most commonly observed in Admiralty Inlet and near the entrance to Prince Regent Inlet and ringed seals fairly uniformly distributed across the study region (Fig. 2). For the remainder of this analysis, we focus on beluga and narwhal since both bowhead and ringed seal had relatively few cells with occurrence.

3.2. Seabirds in TI NMCA

Seabirds were widely distributed across the TI NMCA (Fig. 4). Greater densities of seabirds were encountered near the southeast and northwest tips of Bylot Island, the northeast tip of Somerset Island, and south of Coburg Island, all of which are regions close to major, mixed-species seabird colonies. This pattern was particularly evident for black-legged kittiwake and thick-billed murre, whereas northern fulmar, which can travel much farther to feed (Mallory et al., 2019), appeared less constrained by colony location. Seabird densities were generally greater in the larger expanses of open water in Lancaster Sound than in the narrow channels of Eclipse Sound or Navy Board Inlet.

3.3. Historic vessel traffic trends

The total annual kilometers traveled by all vessels types in TI NMCA in the past 26 years has more than doubled. In 1990 the total kilometres traveled by vessels was 51,584 km, increasing to 142,111 km in 2018 (Fig. 5). Since 1990, the average vessel traffic has increased with some variation from year to year, including a drop between the years 2000 and 2004 (Fig. 5).

During the baseline period of 1990–2000 vessel traffic remained relatively stable, fluctuating between 51,584 km and 81,969 km with an average of 65,926 km. During phase 1 the total annual distance traveled in Tallurutiup Imanga started to decrease, with the lowest value in 2004 at 44,416 km; the phase 1 average was 54,205 km. The annual average

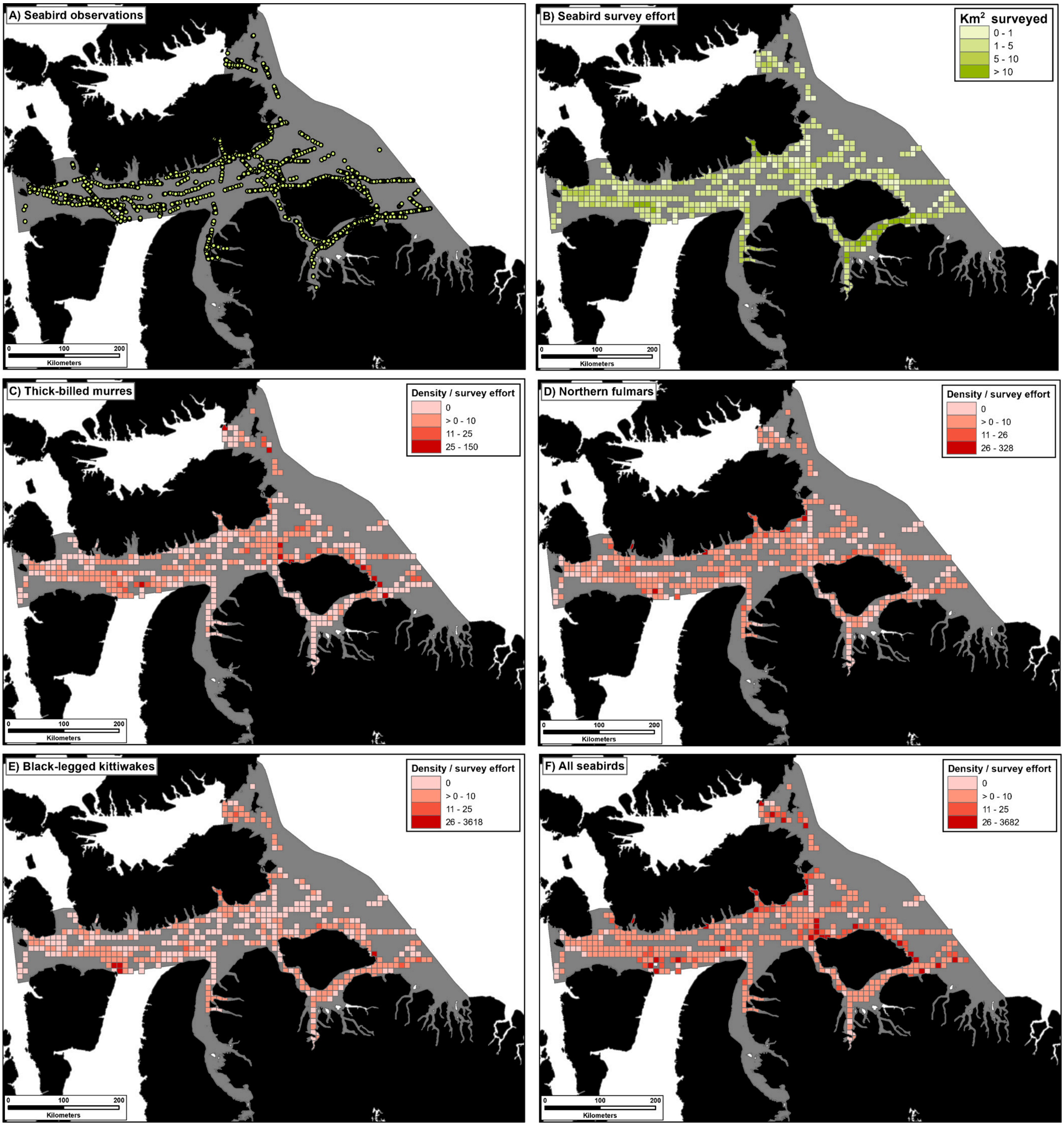

Fig. 4. Distribution of ship-based seabird observations in the Tallurutiup Imanga National Marine Conservation Area (TI NMCA) from 2007 to 2018 (A). Seabird ship-based survey tracks corrected for effort (total km^2 surveyed within each 10 × 10 km grid cell) (B). Spatial distributions of thick-billed murre (C), northern fulmar (D), black-legged kittiwake (E), and all three species combined (F). Data in panels C-F are displayed as density corrected by survey effort (density of individuals divided by km^2 surveyed). Cells with no data within the study area are grey.

traveled in phase 2 was 66,370 km, which was higher than phase 1 and the baseline period. The distances traveled in phase 2 ranged from 57,582 km to 76,753 km. The final phase 3 had the highest annual average distance traveled with 105,446 km and ranging from 68,160 km to 157,820 km.

3.4. Vessel intensity and modeled vessel source noise in TI NMCA

The highest vessel intensity was concentrated in Eclipse Sound and Milne Inlet (Fig. 6). Vessel intensity was also relatively high along the southern and eastern coast of Devon Island, the north coast of Baffin Island and Bylot Island, and near the communities of Arctic Bay and Resolute Bay. Large areas of the TI NMCA had close to zero vessel traffic. Average annual vessel intensity per 10 km grid cell ranged from 0 km/cell to 1896 km/cell, and the only area where intensity exceeded 900 km/cell was in Eclipse Sound and Milne Inlet.

Similar to vessel intensity, the number of potential exposure events from vessel-source noise was greatest in Eclipse Sound and Milne Inlet,

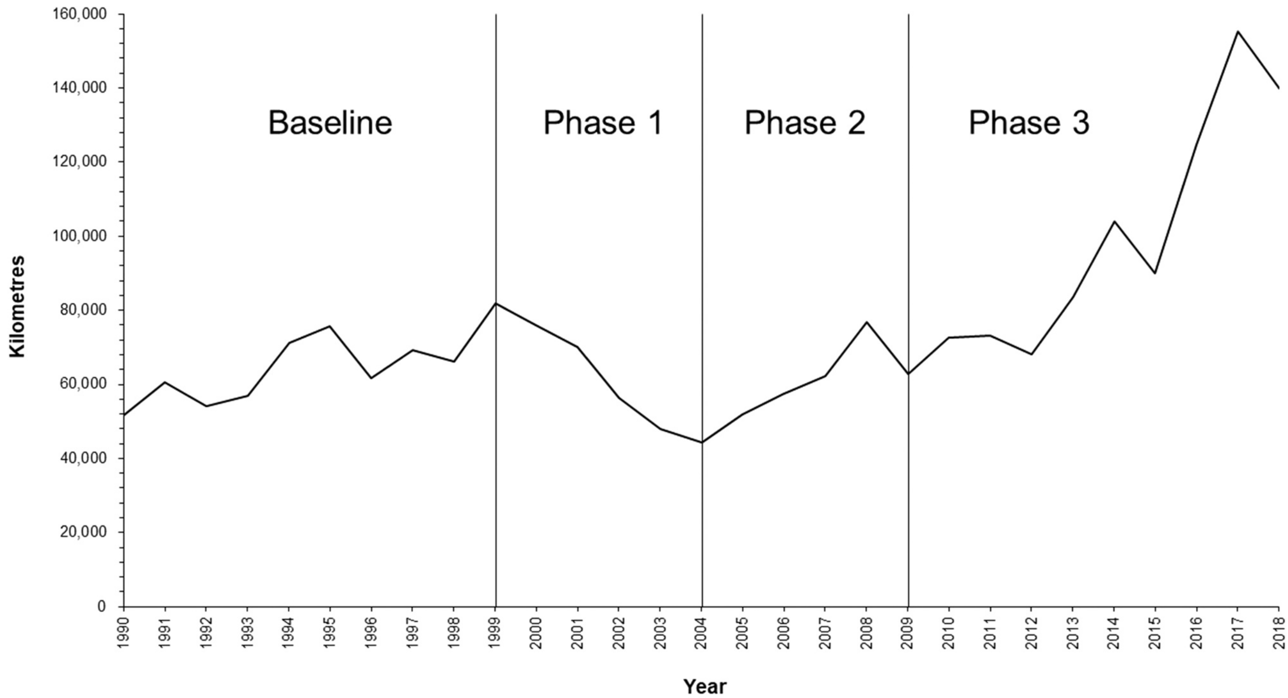

Fig. 5. Total annual kilometres traveled by all vessel types in Tallurutiup Imanga.

and the highest possible number of noise events per grid cell per year of 69 was achieved within this area. No area outside of Eclipse Sound and Milne Inlet had more than 10 noise events/cell per year (Fig. 6).

3.5. Risk to marine wildlife from vessel intensity and vessel-source underwater noise

The highest vessel intensity risk and noise risk to narwhal based on telemetry data occurred throughout Eclipse Sound and Milne Inlet, and according to aerial surveys data, the greatest risk was centered in western Eclipse Sound and Milne Inlet (Figs. 7 and 8). The highest risk to seabirds also occurred at the eastern entrance to Eclipse Sound (Figs. 7 and 8), although all three species had small areas of increased risk spread out throughout TI NMCA. For example, northern fulmar also had increased risk along the south coast of Devon Island, particularly in Croker Bay, and black-legged kittiwake had increased risk around Prince Leopold Island. For beluga whales, the highest vessel intensity and noise risk occurred along the southern shores of Devon Island, particularly in Croker Bay (Figs. 7 and 8), and noise risk was also elevated along the eastern shore of Devon Island.

Vessel intensity and noise risk results were qualitatively quite similar. However, noise risk typically highlighted additional areas of increased risk that were considered low according to vessel intensity (Figs. 7 and 8).

4. Discussion

Tallurutiup Imanga is an important area for marine wildlife, as demonstrated by the numerous whale and seabird hotspots identified in this study, and subsequently, a key area for subsistence hunting activities by Inuit. Disturbance and noise risk from vessels are key concerns for the conservation of these species, and may make wildlife inaccessible to hunters by displacing them from traditional hunting areas (see Carter et al., 2018, 2019). While vessel traffic remains relatively low in much of TI NMCA, traffic has been increasing rapidly over the past few years, and has more than doubled between 1990 and 2018 (Fig. 5; see also Kochanowicz et al., 2021). Most of this increase in traffic is directly linked to vessel traffic associated with Baffinland Iron Mines Corporation's (hereafter referred to as Baffinland) Mary River Mine, which has led to Milne Inlet and Eclipse Sound having the highest levels of vessel traffic not only in TI NMCA (Fig. 6), but in the entire Canadian Northwest Passage (Dawson et al., 2018). The high levels of vessel traffic within Eclipse Sound and Milne Inlet also overlap with hotpots for narwhal and seabirds. Within TI NMCA, other areas outside of Eclipse Sound and Milne Inlet with high overlap between vessel traffic and marine wildlife were along the south and east coast of Devon Island, where vessels overlap with beluga and northern fulmar, and around Prince Leopold Island, where vessels overlap with black-legged kittiwake. Looking to the future, vessel traffic is generally expected to continue increasing as the Arctic becomes more reliably ice-free during the summer. Furthermore, natural resource extraction activities will likely lead to even higher levels of vessel traffic. Baffinland, for example, has proposed to double their output of iron ore at the Mary River Mine, which will increase the number of vessels transiting this area, including the addition of icebreaking during the ice-formation and break-up seasons. This continued increase in vessel traffic in the TI NMCA will translate into increased risk for marine wildlife.

The main impacts of vessel traffic on marine wildlife are ship strikes (especially for bowhead whales; George et al., 2017), physical disturbance (i.e. flushing of seabirds, icebreaking affecting ice seals), exclusion from areas, noise (both underwater and in air), light pollution, chemical pollution including oil spills, and transportation of invasive species that can have ecological consequences (Arctic Council, 2009). Ship strikes may represent an immediate, lethal consequence, although not all ship strikes are lethal (Conn and Silber, 2013), whereas most other vessel impacts have sub-lethal consequences that may act cumulatively with other stressors, especially with repeated exposures through time. For example, underwater noise is known to cause behavioral disturbance to Arctic marine mammals (Halliday et al., 2020a), and may lead to increased stress hormone levels (Watt et al., 2021). Similarly, repeated short term disturbance may lead to reduced time foraging, with implications for health and reproductive success in the long-term. Repeated disturbance in key areas, such as migration routes, may even lead to a shift in the location of these routes or displacement from important foraging areas. Endemic Arctic wildlife are largely naïve to vessel traffic, and may therefore have more extreme responses compared

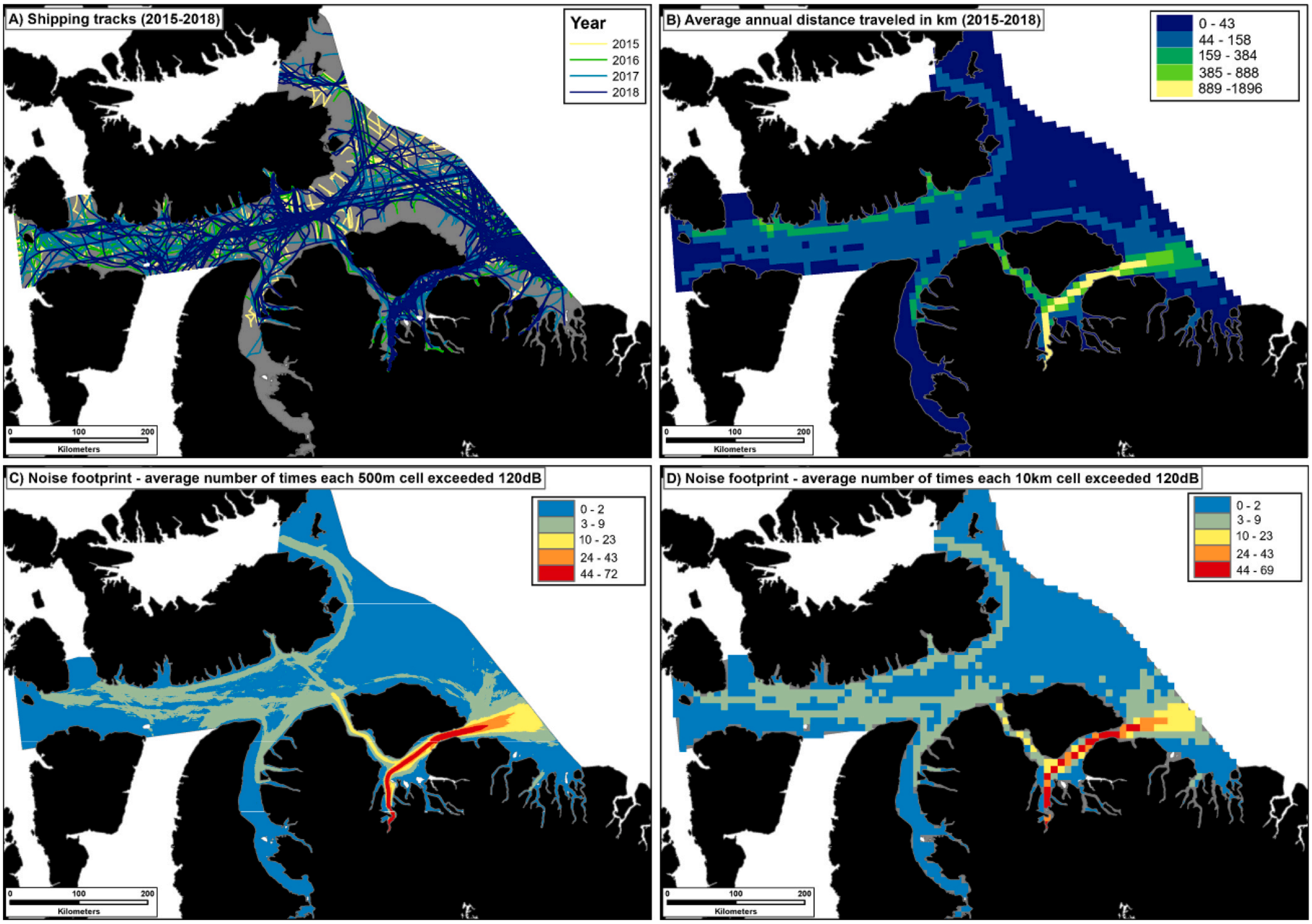

Fig. 6. Vessel tracks in the TI NMCA from 2015 to 2018 within a shipping season from 19 July to 10 October (A). Average distance traveled per year in 10 × 10 km grid cells, based on data from 2015 to 2018 (B). Average number of times per year that each 500 × 500 m cell exceeds 120 decibels (dB) in the TI NMCA from 2015 to 2018 (C). Average number of times per year that each 10 × 10 km cell exceeds 120 dB in the TI NMCA from 2015 to 2018 (D).

to temperate species that are more familiar with vessel traffic (Halliday et al., 2020a). A large oil spill event could also have irreversible negative effects on wildlife populations and the TI NMCA ecosystem, such as previously reported for the Exxon Valdez spill in Alaska (Peterson et al., 2003).

While we clearly identified species-specific regions of highest vessel risk, there are a number of assumptions associated with the risk classification that should be considered. Here, we estimated the level of potential exposure (or co-occurrence) of marine wildlife to vessel intensity and vessel noise, and the level of risk relative to each species. However, other studies have estimated risk by correcting exposure according to the sensitivity of each species (see Hauser et al., 2018). For example, if certain species show stronger reactions to vessel noise or have more negative consequences from overlap with vessels, they would have higher risk values than species who are less sensitive but have similar levels of exposure. Moreover, for vessel traffic and noise, it may not be fair to compare marine mammals and seabirds, given that marine mammals are known to hear and react to vessel noise from great distances in the Arctic (e.g., Finley et al., 1990), whereas no studies have examined long-distance effects of vessel traffic on seabirds. However, at least one study has demonstrated that some non-Arctic seabirds avoid areas with increased noise from seismic surveys (Pichegru et al., 2017), which is evidence that seabirds can react to underwater noise. Furthermore, there is variation in terms of risk between marine mammal species, as bowhead whales are likely more at risk to vessel strikes than narwhal and beluga (Halliday, 2020), but narwhal and beluga both appear to be very sensitive to vessel noise (Finley et al., 1990; Halliday et al., 2019). Weighting our exposure (i.e. risk) estimates by species-specific sensitivity is beyond the scope of this study, but should be considered in future work. The risk values that we present are only relative to the level of vessel traffic in TI NMCA that overlapped with marine wildlife, and will not translate well to other areas without first considering how much traffic was present. For narwhal, the high risk cells had > 40 vessel noise events per year, whereas for beluga, there were 3–9 disturbance events per year. The few seabird cells with "high risk" had intermediate values between the beluga and narwhal. For this reason alone, comparison between species is difficult due to the species-specific normalization of the risk values. But beyond this, different species also have different sensitivity to risk, as explained above on the reactions of some species to underwater noise. What we are calling high risk for these Arctic species would be low risk for temperate species that are exposed to much higher levels of vessel traffic. Yet given the high sensitivity of some Arctic species to disturbance, the current level of vessel traffic may still represent a significant level of risk. Despite these limitations, we provide the first empirical assessment of vessel traffic risk and associated noise risk to seabirds and marine mammals in TI NMCA to inform management and conservation initiatives in the area.

Unlike temperate and tropical waters, the Arctic has relatively low background sound levels and experiences much lower overall levels of vessel traffic (PAME, 2019). Marine wildlife in the Arctic can therefore detect vessels from farther away compared to other regions (PAME, 2019), and some Arctic species, such as narwhal and beluga, have been shown to react to vessels from > 50 km away (Finley et al., 1990).

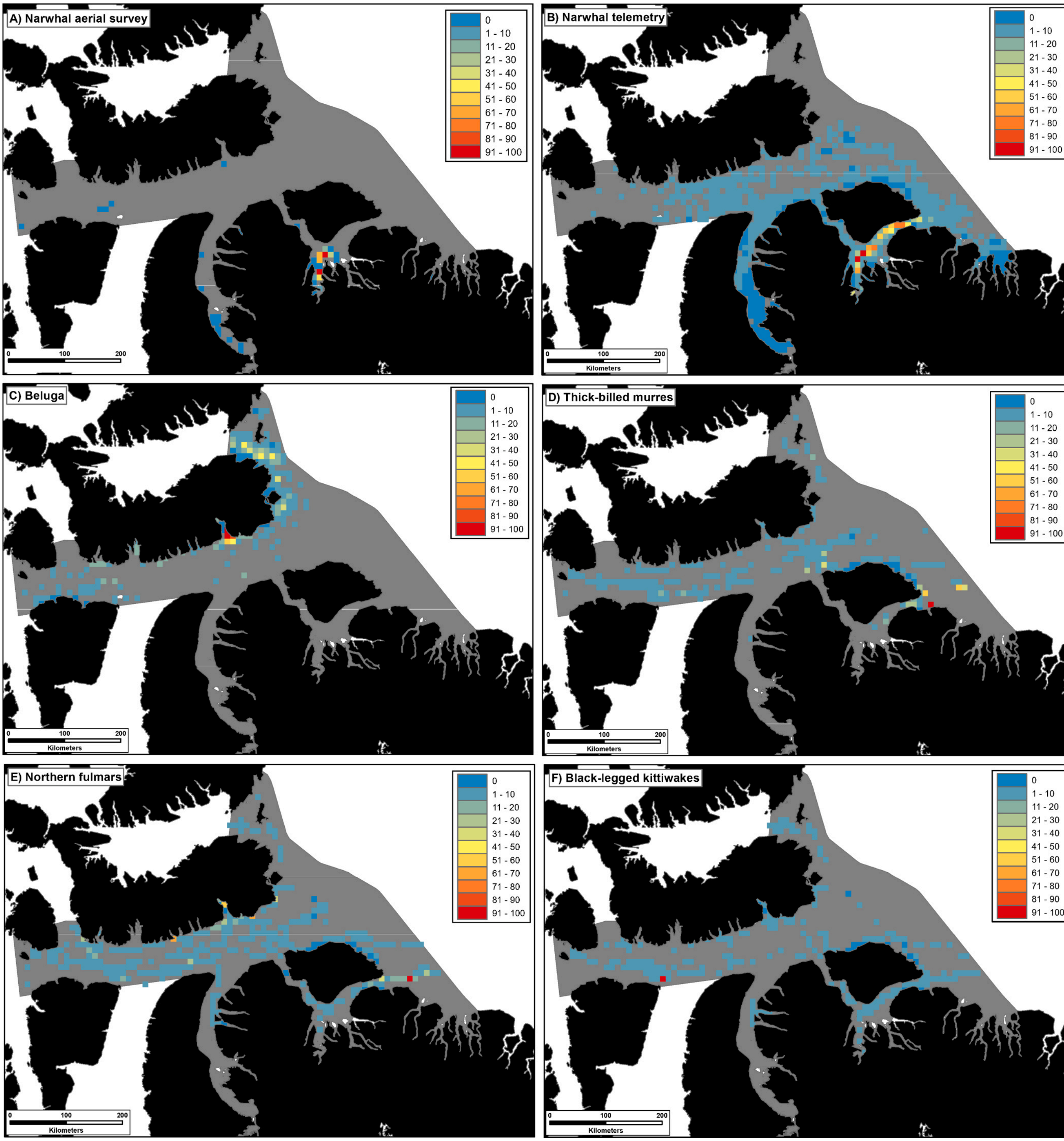

Fig. 7. Vessel intensity risk for narwhal (A and B), beluga whales (C), thick-billed murre (D), northern fulmar (E) and black-legged kittiwake (F) in the TI NMCA. Cells that were not surveyed or where marine wildlife were absent within the study area during surveys are grey.

Similarly, due to the relatively low exposure to vessel traffic, Arctic marine wildlife are also more likely to react to individual vessels than wildlife in waters that continually experience high levels of vessel traffic (PAME, 2019). However, to our knowledge there are only four peer reviewed studies on the behavioral reactions of Arctic marine mammals to underwater noise from vessels (Finley et al., 1990; Halliday et al., 2019; Heide-Jørgensen et al., 2021; Richardson et al., 1985), and no studies on the reactions of Arctic seabirds to vessel noise. This highlights a crucial need to conduct more research to develop thresholds for behavioral disturbance for all of these species. In fact, while marine mammals have a general noise disturbance threshold of 120 dB re 1 μPa (National Marine Fisheries Service, 2016; Southall et al., 2007), which does not account for context- or species-specific responses, there are no established thresholds for behavioral disturbance to seabirds. Studying the effects of noise on seabirds should therefore be a high priority. More work is needed on measuring exposure of Arctic marine wildlife to vessel traffic and underwater noise. Modeling and mapping exercises such as this (see also Halliday et al., 2021; Kochanowicz et al., 2021; Wong et al., 2018) provide a coarse representation of potential exposure, but studies that track both animals and their exposure to vessel traffic in real-time are required to estimate and refine vessel risk at a finer-scale.

The impacts of vessel traffic on marine wildlife are likely to vary

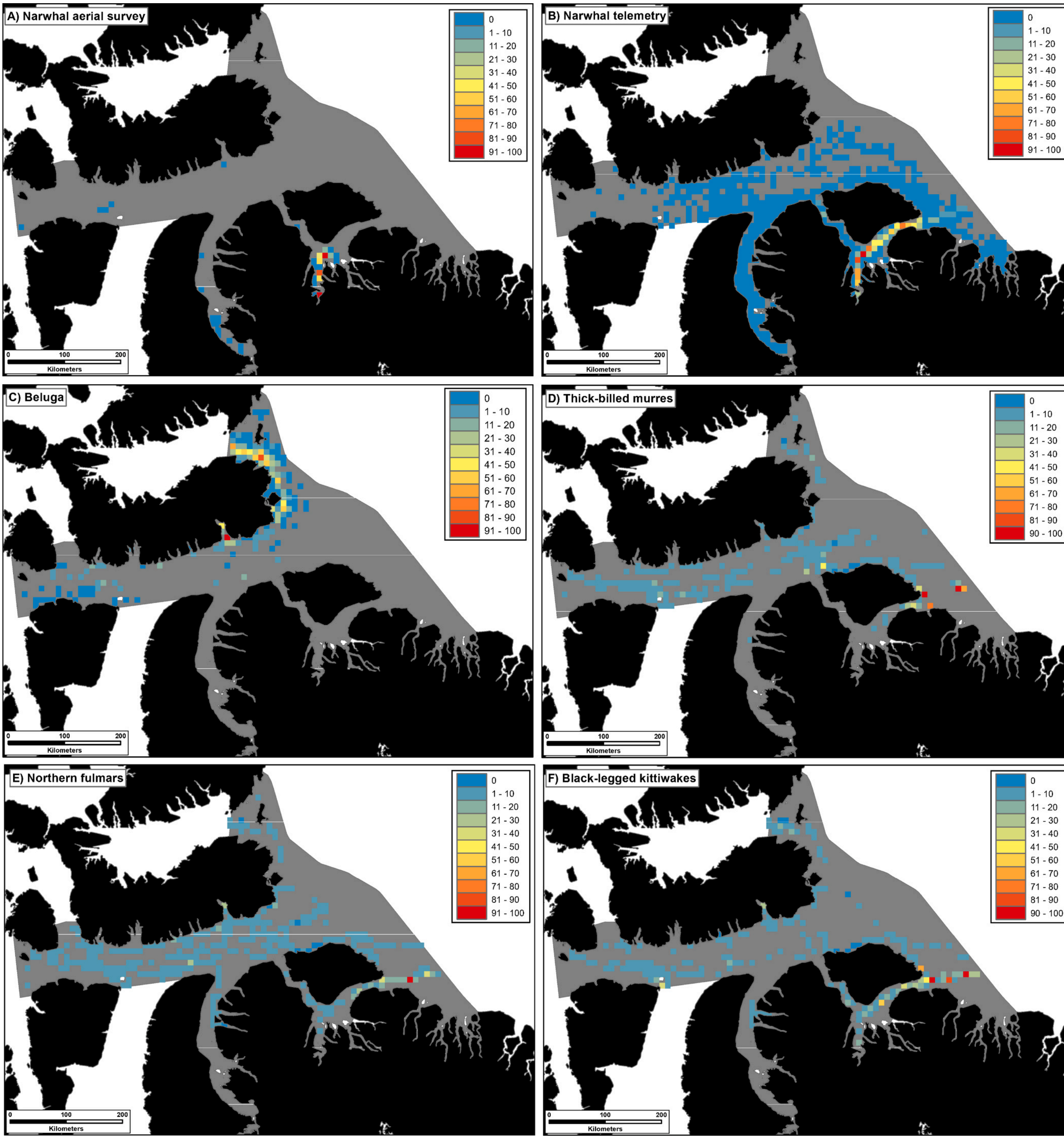

Fig. 8. Level of risk to high noise exposure (≥ 120 dB) for narwhal (A and B), beluga whales (C), thick-billed murre (D), northern fulmar (E) and black-legged kittiwake (F) in the Tallurutiup Imanga National Marine Conservation Area (TI NMCA). Cells that were not surveyed or where marine wildlife were absent within the study area during surveys are grey.

significantly during the open water season due to temporal variation in both vessel traffic and marine wildlife, including temporal changes in the sensitivity of wildlife to disturbance, such as during critical life history events like calf rearing. Although the open water season, and therefore the shipping season, runs from late July to early October in the Canadian Arctic, most of that traffic is concentrated in late August and early September (Halliday et al., 2021, 2020b). Arctic cetaceans and seabirds tend to be within their summer foraging habitat in July and August, but often begin their autumn migration towards their winter habitat in September or October (e.g., Frederiksen et al., 2016; Halliday et al., 2021; Hauser et al., 2017; Laidre et al., 2004; Mallory et al., 2008). Risk to marine wildlife from vessel traffic is therefore expected to be greatest only during the times when both wildlife and vessels are active in the same areas. This temporal aspect was beyond the scope of this study because the different wildlife datasets were collected at different temporal scales: marine mammal telemetry was generally available for July to October, although July typically had fewer points; narwhal aerial surveys were only in August; and seabird surveys were collected in July through October, although data collection tended to be concentrated in August and September. In a preliminary analysis not presented in this

Table 2
Median broadband vessel source levels from the Port of Vancouver's ECHO program and for additional vessel classes from Veirs et al. (2016).

Source of data	Vessel category	N	Source level (dB re 1 μPa @ 1 m)
ECHO Program	Bulk carriers	1728	188.3
ECHO Program	Cruise ships	81	179.5
ECHO Program	Government and icebreakers	12	192.6
ECHO Program	Tankers	292	187.4
ECHO Program	Tugs	582	180.8
Veirs et al. (2016)	Fishing	65	164
Veirs et al. (2016)	Military	113	161
Veirs et al. (2016)	Recreational	41	159

study, we did examine seasonal patterns in narwhal telemetry data by month, and the general hotspots in Admiralty Inlet, Eclipse Sound, and Milne Inlet remained consistent. This suggests that the hotspots identified by aerial surveys and telemetry for narwhal in our study are comparable, despite the different temporal scope. Future work should therefore assess the variations in risk to wildlife at finer temporal scales (i.e. weekly or monthly) throughout the shipping season.

The different methods used to delineate marine wildlife distributions in this study each have their own unique limitations and strengths. Satellite telemetry samples a small number of individuals in a population which may not necessarily represent the movement patterns of other individuals in the population; however, long time series of individual movements and distribution are obtained from telemetry. Aerial surveys cover a large spatial area and sample a large number of individuals in the population, but represent only a brief snapshot in time. Ship-based seabird surveys represent surveys at specific points in space and time with a limited detection radius around the ship, but the sheer number of observations is a definite strength of this method. For most of the species studied here, we only have a single observation methodology, so cannot assess the accuracy of the results. However, for narwhal, we have both telemetry and aerial survey data, and for both data types, high density areas for narwhal are shown in Eclipse Sound, Milne Inlet, and Admiralty Inlet, although the exact locations of high density cells within those areas does vary between methodologies. For example, aerial survey data shows that Milne Inlet, but not Eclipse Sound, is a high density narwhal area, whereas telemetry shows that the high density narwhal area extends throughout Eclipse Sound. The limitations of the marine wildlife density data are then transferred to our risk analysis, since high density would be high risk cells if they overlap with higher vessel traffic. Risk based on narwhal aerial surveys shows that only Milne Inlet is a risk hotspot, whereas telemetry data shows that both Milne Inlet and much of Eclipse Sound are risk hotspots. Our results must therefore be interpreted with some caution, since any biases in underlying data are transferred to the risk calculations. Despite these limitations, the two methodologies do confirm that the area with the highest vessel risk for narwhal is in Milne Inlet.

There are many options available to manage vessel traffic and reduce its impact on marine wildlife (McWhinnie et al., 2018). The most effective for wildlife is to exclude vessel traffic from important sites, either through avoidance areas or vessel routing (i.e. transportation corridors) that circumvent the important area. However, vessel exclusions are the most difficult form of management measure since many vessels simply cannot be excluded from certain areas. For example, marine vessels are the main method for community resupply in the Canadian Arctic. Similarly, spatially constricted areas, such as channels between islands, often leave no options for re-routing if the vessels have to follow those routes. This is particularly apparent for the Mary River Mine, where current infrastructure only allows iron ore to be shipped through Milne Inlet and Eclipse Sound, directly through important areas for narwhal and seabirds. Another vessel management option is slowing the speed that vessels travel. This generally reduces the underwater noise levels from most vessels (MacGillivray et al., 2019), thereby reducing the radius of noise impacts around the vessel. Slowdowns also reduce the likelihood and lethality of vessel strikes (Conn and Silber, 2013; Laist et al., 2001). However, reducing the speed of vessels will not necessarily reduce the number of disturbance events, and would likely have very little impact on the results presented in this study. A final option is to develop a quota system, where only a certain number of vessels can transit through an area, and perhaps these vessels should also travel slowly. For example, Glacier Bay National Park uses a quota system to limit the number of cruise ships in the area (McKenna et al., 2017). In this way, managers can limit the number of disturbance events to some acceptable level while still letting some vessel traffic into an area. Under this model, all community resupply vessels would likely be allowed to enter, but other vessels that are not essential would fall under the quota system.

The TI NMCA, which was designated to protect an important area for marine wildlife and for Inuit subsistence hunting and culture, is experiencing the greatest increase in vessel traffic in all of the Canadian Arctic. This study provides an assessment of the potential exposure of cetaceans and seabirds to vessel disturbance and vessel noise, and highlights hotspots for potential exposure in Eclipse Sound and Milne Inlet (narwhal and all seabirds), as well as along the southern and eastern coasts of Devon Island (beluga and northern fulmar) and at Prince Leopold Island (black-legged kittiwake). Future work should continue to document changes in the intensity and distribution of vessel traffic, and should similarly monitor the distribution and abundance of marine wildlife to assess any changes in distribution and exposure to vessel traffic. Studies are also urgently required on the impacts of vessel traffic and vessel noise on Arctic seabirds. This information will help provide evidence for managers of TI NMCA on the risks of vessel traffic to marine wildlife, allowing them to set management measures and monitoring priorities.

CRediT authorship contribution statement

William D. Halliday: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jackie Dawson**: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **David J. Yurkowski**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Thomas Doniol-Valcroze**: Data curation, Formal analysis, Writing – review & editing. **Steven H. Ferguson**: Conceptualization, Data curation, Writing – review & editing. **Carina Gjerdrum**: Data curation, Writing – review & editing. **Nigel E. Hussey**: Writing – review & editing. **Zuzanna Kochanowicz**: Formal analysis, Writing – review & editing. **Mark L. Mallory**: Conceptualization, Writing – review & editing. **Marianne Marcoux**: Conceptualization, Data curation, Writing – review & editing. **Cortney A. Watt**: Conceptualization, Data curation, Writing – review & editing. **Sarah N.P. Wong**: Conceptualization, Formal analysis, Data curation, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Vessel noise modeling

Estimating propagation loss

The propagation loss of sounds propagating away from a source vessel were modeled throughout the TI NMCA to identify how sound travels differently across this study area. Of particular importance were sites differing in bathymetry or proximity to land. Propagation loss of different classes of vessels was calculated using the software dBSea 2.0 (Irwin Carr Consulting, Northern Ireland). Propagation loss typically depends on four main factors: the source level of the noise, the sound speed profile of the region, bottom sediment type, and bathymetry. We accounted for all four of these variables when modeling (see below).

Median vessel source levels in $^1/_3$-octave bands were obtained from the Port of Vancouver's listening station (ECHO Program) for the following vessel categories: bulk carrier, cruise ship, government research vessel, tanker, and tug (see Table 2). Average broadband source levels for military, recreational, and fishing vessels were obtained from Veirs et al. (2016) (Table 2), but were not used for the detailed acoustic propagation modeling.

The average sound speed profile for the study region was calculated based on conductivity-temperature-depth (CTD) measurements taken by the research vessel CCGS Amundsen. The mean CTD and sound speed values at each meter of depth were calculated from the data from 22 different CTD casts aboard the Amundsen in 2014.

For the bottom sediment type, one single sediment value was used for the entire region. Letaïef et al. took sediment samples across the Canadian Arctic Archipelago, aboard the Amundsen in 2014. The samples were collected at specific spatial points and further interpolated; the average sediment type for this region was identified as silt (Letaïef, 2019; Letaïef et al., 2018).

Bathymetric data was obtained from the International Bathymetric Chart of the Arctic Ocean at a 500 m spatial resolution (Jakobsson et al., 2012). These data are the most recent and most accurate data currently available for the Arctic Ocean at a broad spatial scale.

Using the four inputs mentioned above, sound propagation was modeled using vessel positions along major routes in the region, identified using satellite AIS data. Vessels positions were placed between 20 and 50 km apart while also ensuring that the bathymetric characteristics were included. The model estimates received levels every 500 m away from the source of noise along eight radial slices (45° separation) and 10 m depth increments. The modeling accounted for frequency-dependent attenuation and propagation of sound by modeling each 1/3 octave band, and used two different models to calculate propagation: normal modes for low frequency noise sources (12.5 Hz to 1.2 kHz) and ray tracing for high frequencies (1.6–32 kHz). Propagation loss values were estimated by examining broadband received level by distance out to a maximum distance of 25 km across all radial slices, fitting a logarithmic line of best fit to the data, and estimating the slope coefficient of the logarithmic line as the transmission loss value. This was done for four different vessel classes: bulk carriers, cruise ships, government vessels, and tug boats; the propagation loss estimates for bulk carriers were used for tankers, and the transmission loss estimates for tug boats were used for fishing vessels, recreational vessels, and military vessels.

Monthly vessel noise footprints

Following the estimation of each zone's propagation loss, vessel noise footprints were produced for each vessel track for each vessel within each month of each year from 2015 to 2018 using ArcMap 10.4 software (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute); vessel tracks were built from satellite AIS data (exactEarth, Cambridge, ON). First, a grid of distance values was calculated around each vessel track using 500 m cell size out to a 10 km radius from the vessel track, and each cell was assigned a specific propagation loss value depending on its location and the class of the vessel. The cell containing the vessel track was assigned a distance value of 1 m. The received level (dB re 1 μPa) in each cell was then calculated using the standard received level equation:

$$RL = SL - PL * Distance$$

where RL is received level, SL is the broadband source level for a given vessel class, PL is the propagation loss calculated for different areas in the study region, and Distance is the distance grid.

The received level grid was then converted into a binary raster variable, with a one assigned to any cell where received level was ≥ 120 dB re 1 μPa, and a zero assigned to all cells with received level < 120 dB. 120 dB is the behavioral disturbance threshold for marine mammals as defined by NOAA (National Marine Fisheries Service, 2016; Southall et al., 2007). Binary rasters were then summed for all vessels within a year to estimate the number of times that each 500 m cell exceeded the 120 dB noise threshold within each year. This count represents the number of times within a year that a marine mammal in any given cell could have been exposed to vessel noise that exceeds the 120 dB behavioral disturbance threshold. Outputs for each year between 2015 and 2018 were then averaged, and converted to a 10 × 10 km grid cell to match the same spatial resolution as all other datasets used in the risk analysis. This 10 × 10 km output represents the average times that the 500 × 500 m cells within each 10 × 10 km cell exceed the 120 dB noise disturbance threshold.

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