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ABSTRACT

Tallurutiup Imanga (TI) is a National Marine Conservation Area (NMCA) established in 2019 at the eastern entrance of the Northwest Passage in Lancaster Sound, Nunavut, Canada, to protect 110,000 square kilometres of core habitat for cetaceans. This study examines the potential impacts of underwater noise from increased ship traffic in TI NMCA on three cetaceans: narwhal, beluga whale, and bowhead whale. Automatic Identification System data from 2015 to 2018 were used to spatially analyse ship traffic in the area. Sound propagation loss was modelled using vessel positions along major routes and then used to model vessel acoustic noise outputs. Areas populated by narwhal, beluga and bowhead whales were identified using western science and Inuit knowledge and then overlapped with the vessel noise outputs. Results indicate that an increasing number of ships are transiting important habitat areas for cetaceans and that this has resulted in some areas where the National Oceanic and Atmospheric Association 120 dB behavioural threshold for marine mammals has been exceeded. This suggests that in some areas of TI NMCA ship noise may negatively impact marine mammal hearing and behaviour, with the highest potential exposures in Eclipse Sound and Milne Inlet.

1. Introduction

Marine shipping in the Canadian Arctic has been increasing over the past three decades in large part due to global climate change and reductions in sea ice extent and thickness [1–3]. The commercial viability of an increasingly ice-free Northwest Passage (NWP) has garnered significant international interest. Many commercial operators are attempting transits, including historic sailings of cargo vessels such as the Nordic Orion (traversed NWP in 2011), the Nunavik (2014) and the non-ice strengthened cruise ship the Crystal Serenity (2016, 2017)(also see [4]). Increases in ship traffic in the Northwest Passage [2,5], may lead to an increase in underwater noise pollution in Tallurutiup Imanga (TI) National Marine Conservation Area (NMCA), which could pose a major threat to marine mammals (i.e. cetaceans) including narwhal, beluga, and bowhead whales [6].

TI is located at the eastern entrance to the Northwest Passage and became an NMCA in August 2019 because of its rich ecological and cultural significance [7,8], and for its high biological productivity [9–11]. Two large polynyas (the Lancaster Sound Polynya and the Bylot Island Polynya) facilitate open water even in the winter [10,11], thus creating an ideal habitat for cetaceans. Inuit coastal communities within and adjacent to TI NMCA have expressed concerns about the impact of

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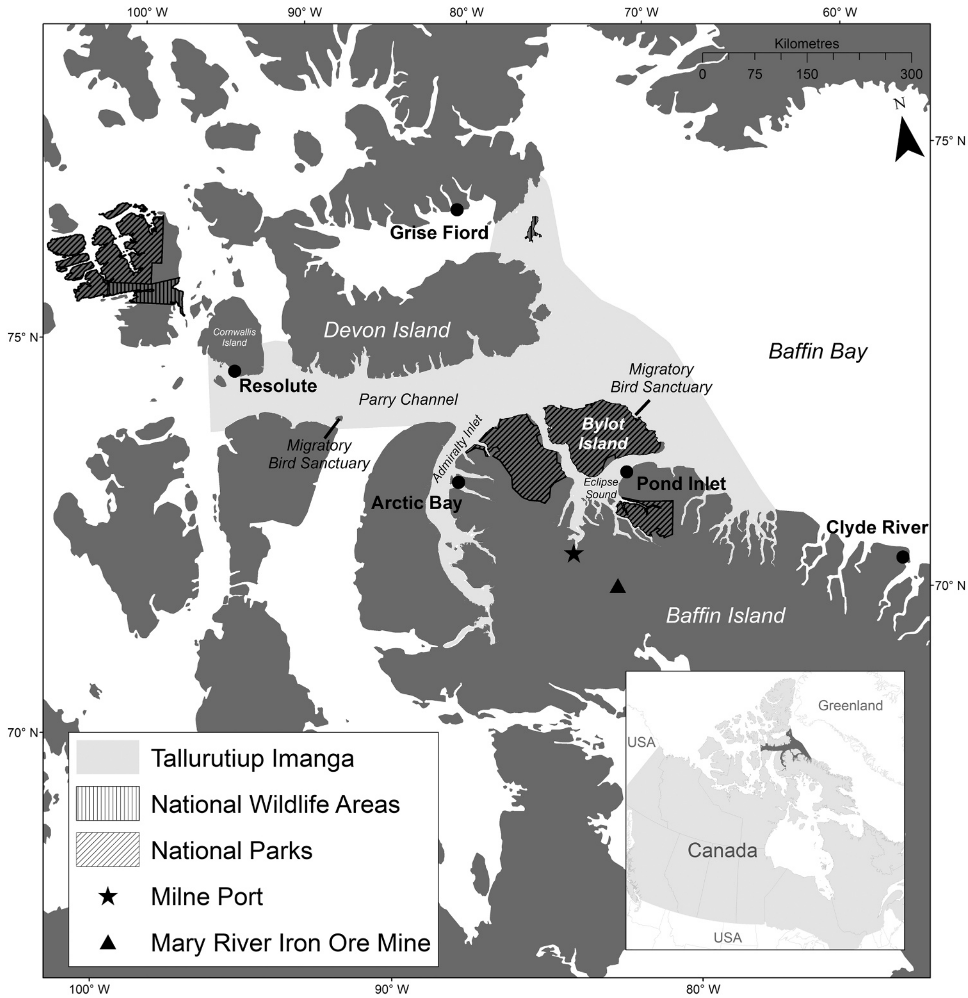

Fig. 1. Map of Tallurutiup Imanga in Nunavut, Canada, the surrounding communities, protected areas and the Mary River Iron Ore Mine.

increased shipping activity on this important cetacean habitat [12,13]. Specifically, Inuit are concerned about ship source noise causing habitat abandonment [12,13] that will have cascading implications for subsistence hunting, livelihoods, food security, and health [14–17]. An understanding of the full range of risks to cetaceans from ships in the Arctic is unclear [18,19] as there are few existing studies that examine the impact of ship-source noise in ice covered areas [6,20–26].

There is a growing trend in ecological research and management across the globe, to mobilise multiple knowledge systems and the unique contributions each knowledge system brings; culminating in enhanced and deepened understanding [27–31]. The multiple evidence approach (MEB) holds that western scientific research, and Indigenous knowledge systems are regarded to engender different "manifestations of valid and useful knowledge" [27] which can generate new insights and innovations through complementarities. When mobilised in these complementary, parallel fashions Inuit knowledge and western science can add new dimensions to understanding ecological information about wildlife and lead to novel and more effective management applications [29,31].

In Canada, it is a policy and legal requirement that Indigenous knowledge is considered in resource management [32,33]. Inuit involvement in management decisions, and preservation of cultural customs, practices, and expression within TI NMCA are enshrined in the TI NMCA Inuit Impact and Benefit Agreement (IIBA) [8]. In Article 1.5 [ibid.] of the IIBA it states that "*Inuit elders' and Inuit knowledge holders' views, expertise and understandings of the environment should, to the fullest extent possible, be applied to encourage the wise use of wildlife, on which Inuit depend, and this traditional knowledge and understanding will be imparted to younger generations*".

In response, this study considers both Inuit and western scientific knowledge of marine mammal distribution to understand the potential impact of ship-source underwater noise for narwhal, beluga and bowhead whales in TI NMCA. This is undertaken by first examining the spatial and temporal trends in vessel traffic and modelled underwater noise by using satellite Automatic Identification System (AIS) data. An assessment is then made of overlaps between the locations of vessel traffic and activity areas of *Delphinapterus leucas* (beluga whales), *Monodon monoceros* (narwhals) and *Balaena mysticetus* (bowhead whales), based on both western scientific and Inuit knowledge. Finally, relevant mitigation strategies are identified and options proposed for consideration in the management of TI NMCA.

2. Data and methods

2.1. Study area

Tallurutiup Imanga is located in the eastern Canadian Arctic, within the territory of Nunavut, between Devon Island and Baffin Island;

Table 1
Category and number of vessels tracked in TI NMCA over the study period 2015–2018, and their respective noise source level.

Vessel category	Number of vessels	Median source level (dB re 1 μPa @ 1 m)
Cargo vessels[a]	1728	188
Cruise ships[a] (Passenger ships)	81	180
Tankers[a]	292	187
Tugs (Tug/Port, Dredger, Barge)[a]	582	181
Government and icebreakers (Research, Search and Rescue)[a]	12	192
Fishing vessels[b]	65	164
Military vessels[b]	113	161
Recreational (Local, Pleasure Crafts, Sailing)[b]	41	159

[a] ECHO Program;
[b] Veirs, Veirs & Wood (2016).

spanning approximately 110,000 km^2. It is approximately 714 km long with areas extending into Baffin Bay, Admiralty Inlet and several adjacent inlets (see Fig. 1).

On August 1, 2019, the Governments of Canada and Nunavut, and the Qikiqtani Inuit Association (QIA) signed an IIBA to officially establish TI as a National Marine Conservation Area [8]. There are five communities in and around TI NMCA: Arctic Bay, Clyde River, Grise Fiord, Pond Inlet, and Resolute, as well as two National Parks, two Migratory Bird Sanctuaries, and two National Wildlife Areas (Fig. 1). The port for the Mary River Iron Ore Mine, one of the world's richest iron ore deposits, is located within TI NMCA at the south end of Eclipse Sound, and since operations began in 2014 ships from the mine have been passing through TI NMCA [34].

2.2. Ship traffic analysis in TI NMCA

Ship traffic trends in TI NMCA from 2015 to 2018 were analysed using satellite-derived AIS data, which is based on an automated tracking system fitted on ships. The system broadcasts information relating to the position of ships (i.e., dynamic messages), and the ship itself (i.e., static messages) [35]. Data were limited to the annual shipping season, defined here as July 19 through October 10 (84 days), based on the first and last days that ships were recorded each year (excluding some outliers for the end of the season). AIS allows managers (i.e., Canadian Coast Guard, Transport Canada) and researchers to track vessel movements and is essential to maritime safety. A limitation is that some smaller vessels do not carry AIS responders and were not accounted for in this study.

For this project, AIS data from exactEarth were provided by the Marine Environmental Observation, Prediction and Response Network (MEOPAR). The data contained multiple position reports (dynamic messages) per day for each ship, so ship track lines with properly formatted time stamps were created. Data were grouped by vessel category and size (Table 1). The maximum distance and time threshold between points was chosen as 300 min or 50 nautical miles. Any gaps in vessel track lines were manually corrected by matching the Maritime Mobile Service Identity (MMSI) number of the lines on either side of the gap, and connecting the two lines with a straight line that followed the rest of the ship traffic in that region.

The study region was divided into a raster of 10 × 10 km (i.e., 100 km^2) grid cells. The ship tracks derived from the AIS data were used to produce spatial trends in ship traffic, measured as the total kilometres traversed in each of the 100 km^2 cells in the study region, by year.

2.3. Acoustic modelling of ship traffic in TI NMCA

A vessel noise output is an estimation of the instantaneous noise level produced by a ship along its track, and the propagation of noise perpendicular to the vessel track. The vessel noise output was estimated using two steps: first, detailed acoustic propagation modelling was used to estimate different zones of propagation loss throughout the study area; and second, received levels of underwater noise around each ship track were estimated based on the zones of propagation loss and average source levels for different vessel categories. The details of these steps are outlined below.

2.3.1. Propagation loss

Median vessel source levels in 1/3 octave bands were obtained from the Port of Vancouver's listening station (ECHO Program) for the following ship categories, based on their acoustical characteristic: cargo (which also include bulk carriers), cruise ship, government and icebreaker vessel, tanker, and tug (Table 1). Average broadband noise source levels for military, recreational, and fishing vessels were obtained from Veirs, Veirs, & Wood [36] (Table 1), but were not used for the detailed acoustic propagation modelling.

The propagation loss of individual ship categories was modelled throughout TI NMCA. Propagation loss is defined as a measure of the reduction in sound intensity as sound travels farther from a source [37]. The propagation loss of underwater noise from ships was calculated using the software dBSea 2.0 (Irwin Carr Consulting, Northern Ireland) [see 22]. Propagation loss depends on the spectral properties of the noise source, the sound speed profile of the region, bottom sediment type, and bathymetry.

The average sound speed profile (mean sound speed values at each metre of depth) for the study region was calculated based on 22 conductivity-temperature-depth (CTD) measurements recorded at multiple locations by the research vessel CCGS Amundsen in 2014. For the bottom sediment type, one single value for silt was used for the entire region based on the samples that Letaïef et al. [38,39] took across the Canadian Arctic Archipelago from the CCGS Amundsen in 2014. Bathymetric data were obtained from the International Bathymetric Chart of the Arctic Ocean v3.0 at 500 m resolution [40]; these data were the most recent and accurate available for the Arctic at the time of modelling.

Using the four inputs described above (vessel noise source level, average sound speed profile, bottom sediment type and bathymetric data), sound propagation was modelled using vessel positions along major routes in the region identified from the AIS data. Vessels' positions were placed between 20 and 50 km apart, while ensuring that bathymetric characteristics were included. Received sound levels were calculated every 500 m away from the source of noise along 8 radial slices (which equal to 45° separation) out to a maximum distance of 25 km, and at 10 m depth increments. Frequency-dependent attenuation and propagation of sound were controlled for by modelling each 1/3 octave band, and using 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 produced and then averaged across the radial slices for each source position, and then grouped together in 15 different areas based on their average propagation losses (Appendix Table 4).

2.3.2. Vessel noise in TI NMCA

Vessel noise outputs were produced for each track of each vessel by month, during the designated shipping season of July–October from 2015 to 2018. Monthly results were combined for each year. A grid of

Table 2
Cetacean telemetry data details during shipping season (July–October).

Species	Years for which satellite data are available	# Individual whales	Total daily locations
Bowhead whales[a]	2006 – 2016	108	3988
Bowhead whales[b]	2002 – 2011	66	3228
Beluga whales[a]	1995 – 2001	28	1516
Narwhal[a]	1993 – 2017	130	6051

[a] Yurkowski et al. (2018).
[b] Heide-Jørgensen et al. (2017).

500 m cells was created around each vessel track, with each cell was assigned a specific propagation loss value depending on the class of the vessel and the location of the cell. The received noise level in each cell was calculated using the standard received level calculation:

$$RL = SL - PL * Distance \quad (1)$$

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 a raster containing the Euclidean distance to the closest source.

The received noise level grid for each vessel track was 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 behavioural disturbance threshold for cetaceans as defined by the National Ocean and Atmospheric Administration [41]. Although the 120 dB threshold is a bit out-dated and there is a lot of variability and a general lack of information for how marine mammals react to noise [42], particularly in the Arctic [25], the 120 dB threshold at least provides a static threshold to compare against. For Arctic odontocetes that may react to very low received levels of ship noise [20,24,25], the 120 dB threshold represents a moderate noise threshold that is clearly above ambient sound levels, even under very windy conditions, and can be reached at relatively far distances from ships (at least 10 km by some larger ships; [22]). Binary rasters were summed for all vessels within a year to estimate the number of times that each 500 m cell exceeded the 120 dB noise threshold; this was done cumulatively for all vessels, and also for all vessels within a single class.

2.4. Identification of cetacean-populated areas

2.4.1. Western science-identified cetacean-populated areas

The three Arctic endemic cetaceans, beluga whales (*Delphinapterus leucas*), narwhals (*Monodon monoceros*), and bowhead whales (*Balaena mysticetus*) were chosen for the analyses as they are the most commonly encountered species in TI NMCA and for which telemetry data are available. Walruses (*Odobenus rosmarus*), ringed seals (*Pusa hispida*), and bearded seals (*Erignathus barbatus*) are also common in the study area but telemetry data are lacking. Polar bears (*Ursus maritimus*) are also a key marine mammal of the Arctic ecosystem, but the data were not included in this study because there are currently no studies showing the impacts of underwater ship noise on polar bears [6].

Western science-identified cetacean-populated areas were calculated using utilisation distributions. Utilisation distributions, or the use of space [43,44] of beluga whales, bowhead whales, and narwhal were calculated for TI NMCA using satellite telemetry data. The cetacean telemetry data for the region were acquired from a regional compilation [45], and were processed in a state-space model to produce one location estimate per day, per individual [45]. Additional bowhead whale data for whales tagged in Disko Bay, Greenland [46], were combined with the bowhead whale data from whales tagged in the Canadian Arctic [47]. See Table 2 for details of all cetacean telemetry data that were used in this study.

The cetacean data were then used to calculate kernel density estimates (KDE). KDE is a common approach used for assessing ranges of terrestrial and aquatic species [48–52]. For this study KDEs were calculated for each of the three cetacean species in R version 3.5.2 using the ks package (version 1.11.5) [52], with the default bandwidth plug-in to estimate the smoothing parameter. The KDEs were calculated using data from July to October to match the vessel data from the shipping season.

Percent volume contours (PVCs) were used to identify the utilisation distributions (i.e., core use areas) of each species from the KDE. 50% and 95% PVCs were calculated for each cetacean species to provide two different estimates of their utilisation distribution (where 95% is an approximation of their range during the shipping season, and 50% is a closer approximation of important areas of high habitat use). Utilisation distributions were clipped by the outline of the TI NMCA after they were calculated. Although core habitats were the main focus of analysis, we included the 95% PVCs as well because it is comparable with the Inuit-identified cetacean populated areas which are discussed in Section 2.4.2.

2.4.2. Inuit-identified cetacean-populated areas

Areas within TI NMCA that are seasonally populated by narwhal, beluga and bowhead whales, were defined using Inuit knowledge contributed by the Arctic Corridors and Northern Voices (ACNV) project (www.arcticcorridors.ca) [53–55]. Through ACNV, Inuit knowledge of culturally significant marine areas, including location of key marine mammal species, were documented in 14 Arctic communities. Results from two of those communities, located within TI NMCA, are included in this study: Resolute and Pond Inlet [53,54].

The ACNV research methods are described in detail in Dawson et al. [55] where additional methodological details can be consulted if desired. Research participants, recognised as key Inuit knowledge holders in their community, were identified by community organisations (e.g. local Hunters' and Trappers' Associations, Hamlet Councils). In April and September 2016 (Pond Inlet) and March 2019 (Resolute), 24 knowledge holders ($n = 15$ in Pond Inlet, $n = 9$ in Resolute) participated in participatory mapping workshops and interviews. Using a semi-structured interview guide and a structured mapping protocol, participants identified culturally significant marine areas including wildlife habitat areas, hunting areas, and observed locations of marine mammals and other fauna [55].

Following a strict data-management and digitising protocol [55], photographs of the paper maps created during the community visits that were populated with marine mammal observations and culturally significant marine areas (i.e., hand-drawn features: polygons, points and lines), were imported and georeferenced in ESRI ArcMap 10.6. Features were then digitised according to relevant community-identified geographical feature(s) [55]. The culturally significant marine areas that participants identified as populated by narwhal, beluga and bowhead whales [53,54] for July through October were included in this study, and will henceforth be referred to as 'Inuit-identified areas'. These areas include feeding, breeding and calving locations of the three cetaceans of interest in this study, as well as their migratory routes; however, the specific behaviours used in different areas have not been distinguished for this analysis.

2.5. Examining modelled noise exposure within important marine mammal areas

The ship noise (number of times that cells exceeded the 120 dB behavioural threshold), utilisation distributions, and the Inuit-identified cetacean-populated areas were overlain in ArcMap. The overlay process revealed regions of cetacean exposure to underwater noise from vessel traffic and enabled the identification of areas within TI NMCA where cetaceans were more or less likely to be exposed to underwater noise from vessel traffic.

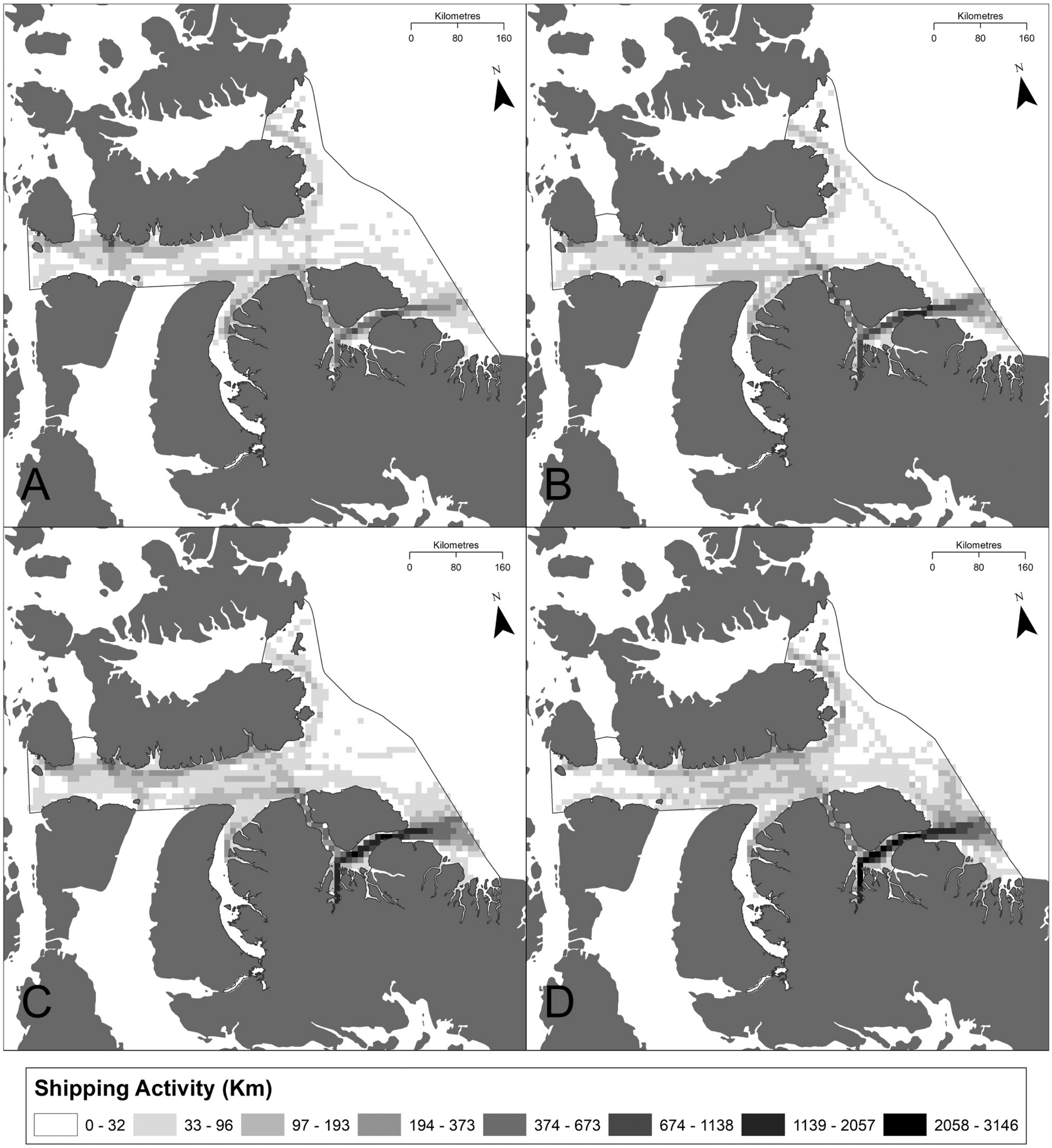

Fig. 2. Total annual distance travelled in km per 10 × 10 km grid cell for all vessel categories for: (A) 2015; (B) 2016; (C) 2017; and (D) 2018 in TI NMCA.

3. Results

3.1. Vessel traffic trends

The total annual kilometres travelled by all vessel categories in TI NMCA was ~76,300 km in 2015, ~98,700 km in 2016, ~138,200 km in 2017, and ~158,100 km in 2018. The average annual kilometres travelled over this four-year period was ~117,900 km.

Cargo, cruise ships, government vessels and icebreakers, and recreational vessels made up the most total annual kilometres travelled. In 2015 cruise ships traversed the most kilometres but were overtaken by cargo ships in the three subsequent years. Subsequently, government vessels and icebreakers were next in terms of total kilometres traversed and their numbers remained relatively stable over the study period. Recreational vessel travel increased from 2015 to 2017 but decreased in 2018. Tanker ships were next in total kilometres traversed. Finally fishing vessels, tugs/barges and military vessels never went above 10,000 km in any one year.

The spatial patterns of total distance travelled for all vessel classes combined are presented in Fig. 2. In 2015 the highest value for kilometres travelled in a 10 × 10 km grid cell was in eastern Eclipse Sound at 830 km, but in 2016 this more than doubled to 1777 km, and then increased again to 2542 km in 2017, and in 2018 reached a maximum of 3145 km. The average distance travelled per grid cell across the TI

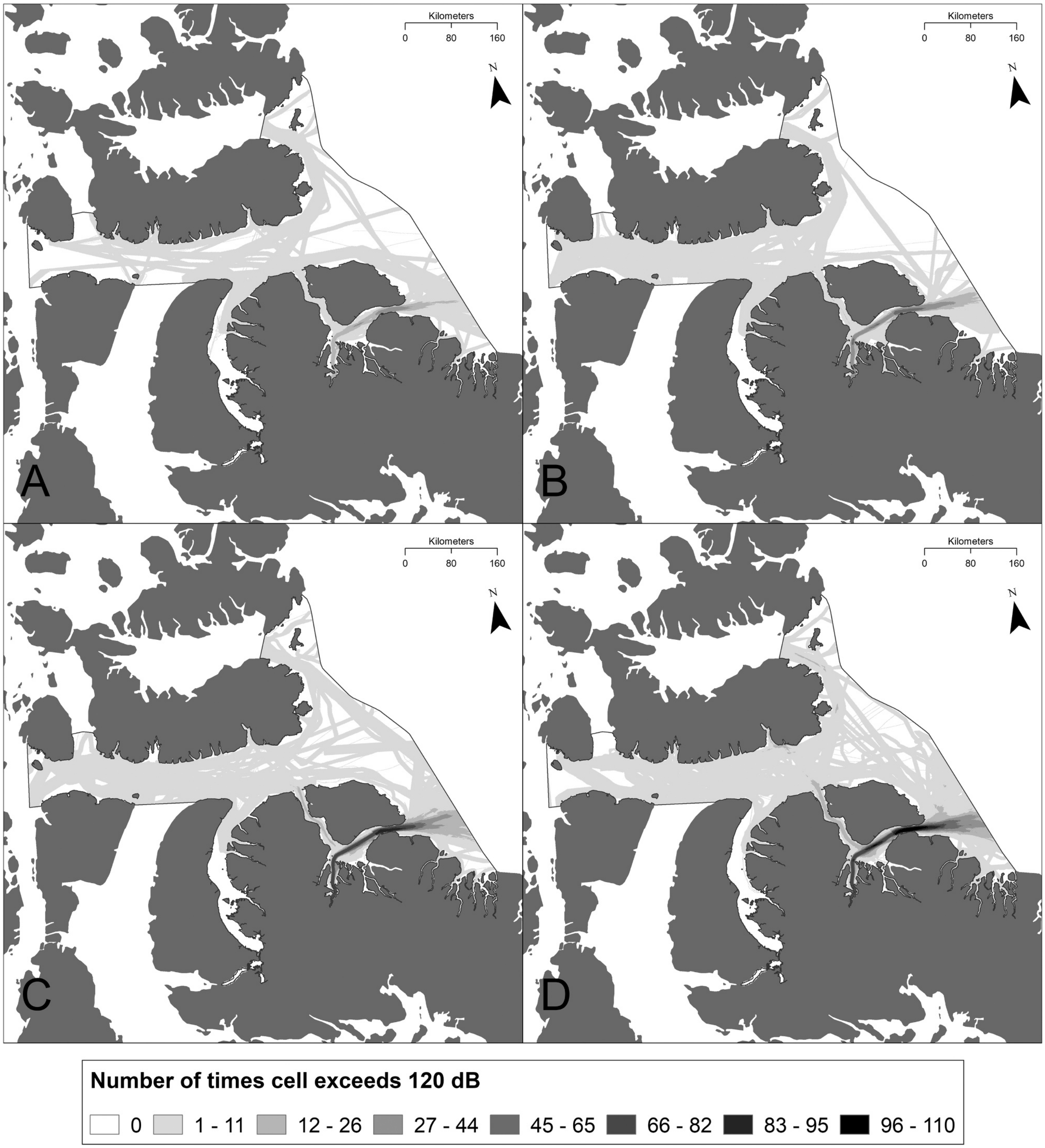

Fig. 3. Total times 500 × 500 m cells exceeded 120 dB for all vessel categories for: (A) 2015; (B) 2016; (C) 2017; and (D) 2018 in TI NMCA.

NMCA was 36 km in 2015, 46 km in 2016, 64 km in 2017, and 74 km in 2018. The area that experienced the most distance travelled by vessels in all four years was Eclipse Sound, to the south of Bylot Island, with the entrance having the highest shipping activity in 2018 and 2017 (maximum values of 1725 and 1526 km, respectively) and less in 2016 and 2015 (maximum values of 1315 and 587 km, respectively). Other notable areas of higher shipping activity over the four years are the southern coastlines of Devon Island near Croker Bay and Beechey Island, the eastern coast of Devon Island (including south of Coburg Island), Resolute, Admiralty Inlet, Parry Channel, and Barrow Strait.

3.2. Modelled ship noise

We use two metrics of modelled ship noise to describe the trends in our analysis. The first is the number of potential behavioural disturbance events (number of times the 120 dB threshold was surpassed) within a 500 m cell. The second is the area covered by cells where at least one potential behavioural disturbance event occurred. These two metrics allow for a description of the intensity of potential behavioural disturbance events, along with the spatial coverage of all potential behavioural disturbance events.

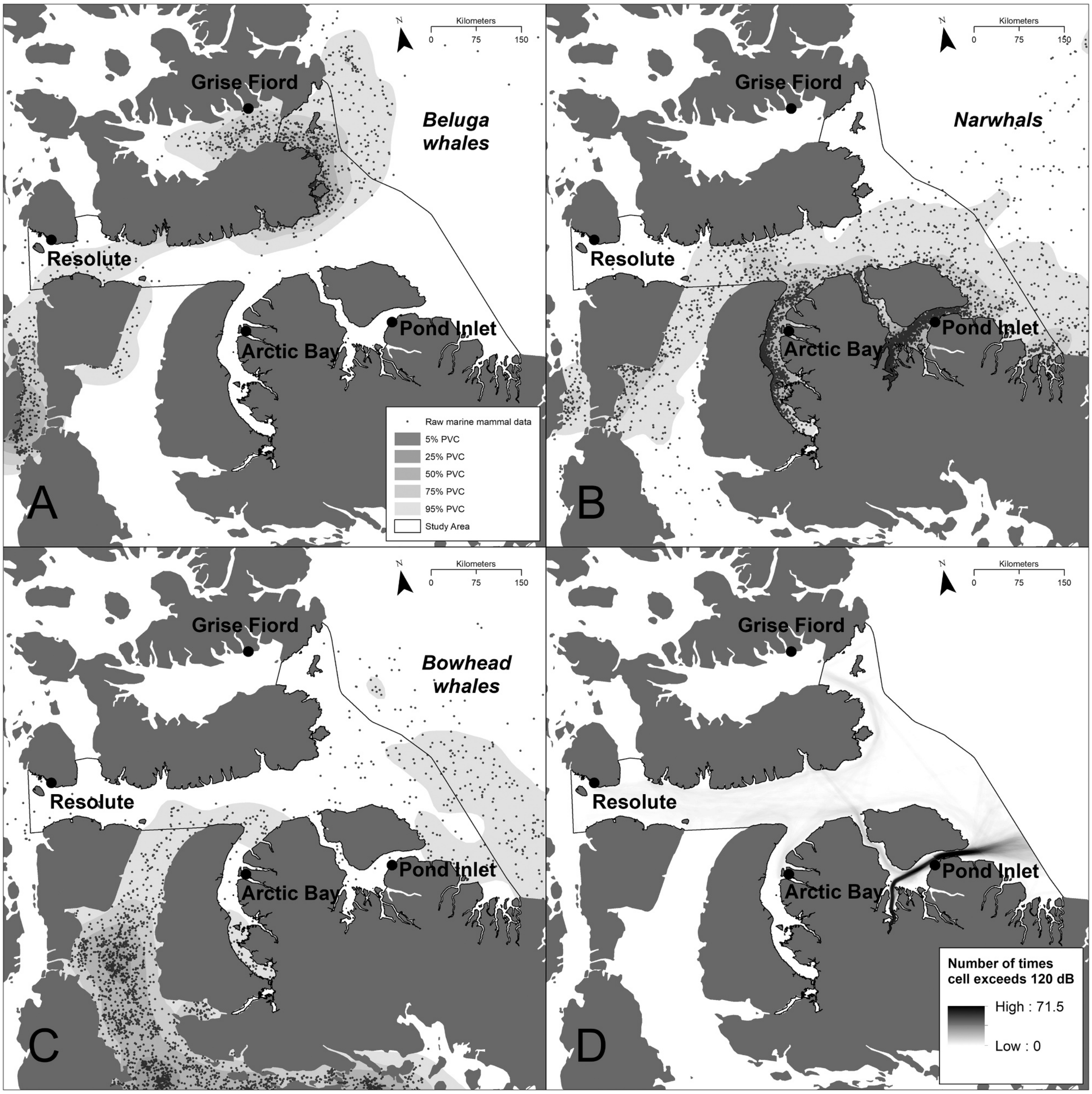

Fig. 4. Relative use (Percent Volume Contours (5, 25, 50, 75, 95)) of TI NMCA for: (A) beluga whales, (B) narwhals, (C) bowhead whales, together with raw cetacean daily location points. Panel D represents the average number of times that each 500 m cell exceeded the value of 120 dB per year, cumulatively for all vessels from 2015 to 2018.

Shipping noise within TI NMCA is presented in Fig. 3, with the greatest number of events with underwater noise levels exceeding the 120 dB threshold occurring in Milne Inlet (the main access point for the Mary River Iron Ore Mine), and Eclipse Sound, both in 2018. In those areas the threshold was surpassed within 500 m cells 34 times in 2015, 55 times in 2016, 93 times in 2017 and 110 times in 2018, the highest throughout the TI NMCA. The maximum number of times in a year (based on the 2015–2018 average) that an individual 500 m grid cell exceeded the 120 dB noise threshold in the entire TI NMCA was 71.5, which was also found in Eclipse Sound (Fig. 4D). The 120 dB threshold was also exceeded frequently at the eastern entrance into TI NMCA near southeastern Bylot Island, and the northeast coast of Devon Island. The area near Devon Island surpassed the threshold 8 times in 2015, 7 times in 2016, 6 times in 2017, and 13 times in 2018.

3.3. Identification of cetacean-populated areas

3.3.1. Western science-identified cetacean-populated areas

Both the 50% PVC and 95% PVC were analysed in this study. Portions of the beluga whale and narwhal 50% PVC areas were located in the TI NMCA (Fig. 4A). The total area of 50% PVC for belugas whales in TI NMCA was ~5800 km^2, of which ~5700 km^2 was off the northeast coast of Devon Island and ~100 km^2 was in Maxwell Bay. The narwhals' 50% PVC area in TI NMCA was larger than that of beluga whales (~13,100 km^2), of which ~7300 km^2 was in Admiralty Inlet and ~5800 km^2 was in Eclipse Sound.

Portions of all three cetacean species' 95% PVC areas were in TI NMCA. The total beluga whales 95% PVC in TI NMCA was ~33,600 km^2. The narwhals 95% PVC area in TI NMCA was the largest at ~76,800 km^2. The bowhead whales 95% PVC area in TI NMCA of

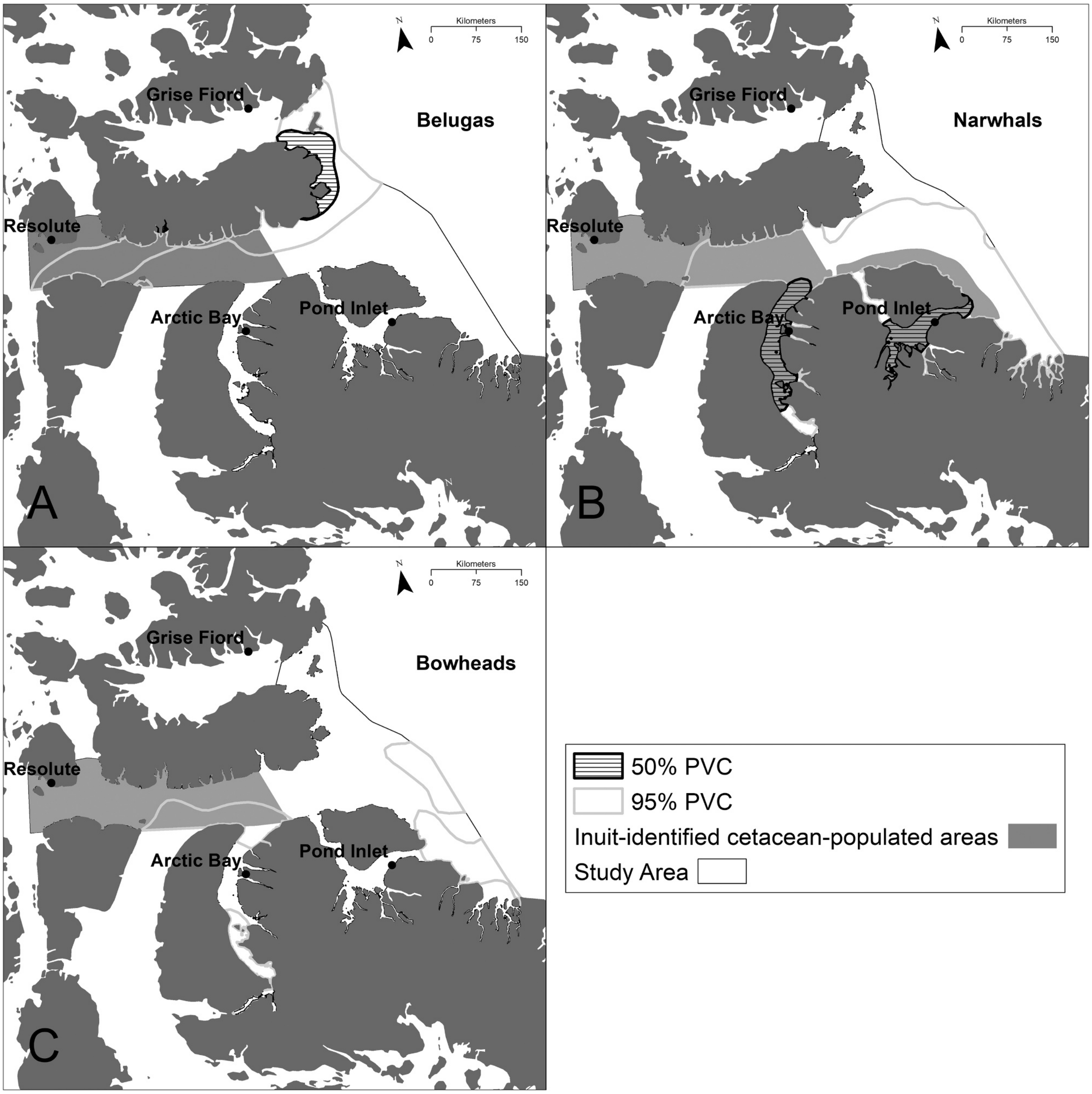

Fig. 5. Spatial comparison between Inuit-identified cetacean-populated areas (from community members in Resolute and Pond Inlet) and cetacean utilisation distributions (based on telemetry results – western scientific knowledge, specifically Percent Volume Contours (PVCs)), where (A) is beluga whales; (B) is narwhals; and (C) is bowhead whales.

~27,500 km^2 was the smallest within the study area.

3.3.2. Inuit-identified cetacean-populated areas

Participants in Resolute identified narwhal, beluga and bowhead whale areas (Fig. 5A, B and C), while Pond Inlet participants identified narwhal areas only (Fig. 5B). The Inuit-identified beluga and bowhead whale use areas (Fig. 5A and C respectively) were concentrated west of TI NMCA, near Resolute. This area was ~36,300 km^2. The Inuit-identified narwhal use areas covered the same western area as the beluga and bowhead whale areas, as well as Admiralty Bay Eclipse Sound and the northern waters surround Bylot Island, bringing the total area to ~60,200 km^2.

3.3.3. Comparison of western science-identified and Inuit-identified cetacean-populated areas

A comparison of the Inuit-identified and western-identified cetacean populated areas is also presented in Fig. 5. The smaller area of the beluga whale core utilisation distribution in Maxwell Bay overlapped with the Inuit-identified beluga whale use area, while the larger beluga whale area of the utilisation distribution on the eastern coast of Devon Island did not overlap with the Inuit-identified beluga whale area (Fig. 5A). Similarly, the 95% PVC overlapped with the Inuit-identified beluga

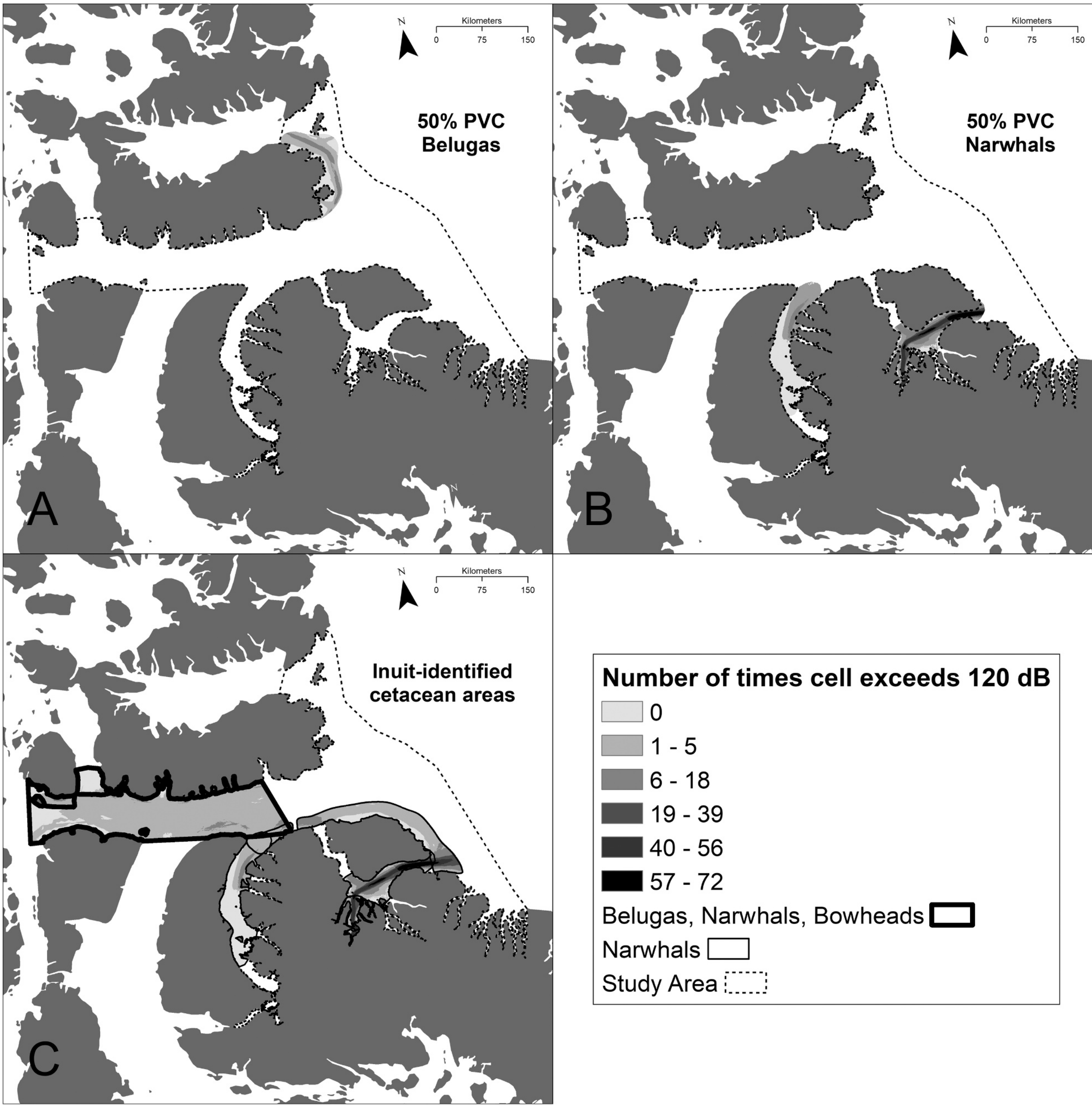

Fig. 6. Average number of times per year from 2015 to 2018 that each 500 m cell exceeded the value of 120 dB, cumulatively for all vessels, in: (A) beluga whale core use areas; (B) narwhal core use areas; (C) Inuit-identified beluga whale and narwhal areas.

whale use area in the west of TI NMCA, but not in the east which is farther away from Resolute. The narwhal utilisation distribution overlapped with the Inuit-identified narwhal use areas, both in Admiralty Inlet and Eclipse Sound (Fig. 5B). The narwhal 95% PVC also corresponded with the Inuit-identified narwhal areas, and extended further north than the Inuit-identified narwhal use areas. The Inuit-identified bowhead whales use areas (Fig. 5C) overlapped with the 95% PVC for bowhead whales, and extended farther west than the bowhead whale utilisation distribution.

3.4. Examination of potential for noise disturbance events for beluga whales, narwhals and bowhead whales

3.4.1. Western science-identified cetacean-populated areas overlapping with vessel noise

The overlap between modelled vessel noise and cetacean areas (both utilisation distributions and Inuit observations) are presented in Fig. 6. The maximum number of times that a 500 m cell exceeded the 120 dB threshold in the beluga whale 50% PVC was 8 in 2015, 7 in 2016, 6 in

Table 3
Areas where vessel noise outputs (all categories combined) exceeded 120 dB in Inuit-identified narwhal, beluga whale and bowhead whale use areas, 95% PVCs and 50% PVCs, in 2015–2018.

Cetacean	Year	Area of potential behavioural disturbance events overlapping Inuit-identified areas in km^2 (% of total Inuit-identified area)	Area of potential behavioural disturbance events overlapping 95% PVC areas in km^2 (% of total 95% PVC)	Area of potential behavioural disturbance events overlapping 50% PVC areas in km^2 (% of total 50% PVC)
Narwhal	2015	32,317 (60%)	45,523 (58%)	7045 (54%)
	2016	41,766 (78%)	47,463 (61%)	8063 (62%)
	2017	41,939 (78%)	55,024 (72%)	7613 (58%)
	2018	40,895 (77%)	60,016 (78%)	7143 (55%)
Beluga whales	2015	18,566 (58%)	19,126 (57%)	3923 (67%)
	2016	27,763 (86%)	22,405 (67%)	3818 (65%)
	2017	28,126 (88%)	23,038 (68%)	3757 (64%)
	2018	26,596 (83%)	24,452 (73%)	4437 (76%)
Bowhead whales	2015	18,566 (58%)	15,967 (57%)	0
	2016	27,763 (86%)	17,371 (61%)	0
	2017	28,126 (88%)	21,779 (77%)	0
	2018	26,596 (83%)	21,561 (76%)	0

2017 and 13 in 2018, for a mean maximum across years of 8.5 (out of a total of 23,328 500 m cells in the 50% PVC) (Fig. 6A).

When examining the cells which exceeded the 120 dB behavioural disturbance threshold by vessel category in the beluga whale 50% PVC, cargo vessels and cruise ship noise outputs exceeded the threshold the greatest number of times compared to other ship types in all 4 yr of this study (Appendix Table 5). Government vessels and icebreakers had the highest area of potential behavioural disturbance events at an average of ~2900 km^2/year, followed by cruise ships at ~2400 km^2/year, cargo ships at 2048 km^2/year, and then tankers at ~1400 km^2/year.

The potential behavioural disturbance events in the narwhal 50% PVC in Eclipse Sound and Milne Inlet were due to mine-related ship traffic (bulk carriers), cargo ships, icebreakers, cruise ships, and tankers. Potential behavioural disturbance events from cargo ships spanned ~5300 km^2/year, followed by government vessels and icebreakers at ~5100 km^2/year, cruise ships at ~3500 km^2/year and tankers at ~3400 km^2/year. The maximum number of times that a 500 m cell exceeded the 120 dB threshold in the narwhal 50% PVC was 34 in 2015, 55 in 2016, 93 in 2017 and 110 in 2018, with an overall average maximum of 72 per year over the period of study (out of a total of 52,428 500 m cells in the 50% PVC).

The highest number of potential behavioural disturbance events for the beluga whale 95% PVC was in 2018 when cruise ships caused 12 events within a single 500 m cell (Appendix Table 6). The maximum ($n = 76$) for both the narwhals and bowhead whales 95% PVC was in 2018, when cargo ships caused 76 potential behavioural disturbance events.

3.4.2. *Inuit-identified cetacean-populated areas overlapping with vessel noise*

The maximum annual value of potential behavioural disturbance events for cetaceans (average annual maximum = 72) occurred in the Inuit-identified narwhal areas (Fig. 6C), compared to beluga and bowhead whale Inuit-identified areas which both had an average annual maximum of 7.5 events (Fig. 6C). The large number of potential behavioural disturbance events for narwhals was due to the high number of incidences in Eclipse Sound, where no bowhead or beluga whales were identified.

Since beluga whale and bowhead whale Inuit-identified cetacean populated areas are the same surface area, they will be presented together. The maximum number of times that a 500 m cell exceeded the 120 dB threshold in the Inuit-identified beluga whale and bowhead whale populated areas was 8 in 2015, 9 in 2016, 11 in 2017 and 12 in 2018, for a mean maximum across years of 10 (out of a total of 128,503,500 m cells in the beluga Inuit-identified area) (Fig. 6C).

In the Inuit-identified beluga whale and bowhead whale populated areas, cargo vessels and cruise ship noise outputs exceeded the 120 dB behavioural disturbance threshold the greatest number of times compared to other ship types in all 4 years of this study (Appendix Table 7). Government vessels and icebreakers had the highest area of potential behavioural disturbance events at an average of ~18,200 km^2/year, followed by cruise ships at ~11,700 km^2/year, cargo ships at ~9800 km^2/year, and then tankers at ~6500 km^2/year.

The potential behavioural disturbance events in the Inuit-identified narwhal-populated area were the highest of the three cetaceans. Potential behavioural disturbance events from government vessels and icebreakers spanned ~26,300 km^2/year, followed by cargo at ~19,700 km^2/year, cruise ships at ~19,200 km^2/year and tankers at ~12,00 km^2/year. The maximum number of times that a 500 m cell exceeded the 120 dB threshold in the Inuit-identified narwhal-populated area was 20 in 2015, 37 in 2016, 72 in 2017 and 76 in 2018, with an overall average maximum of 51 per year over the period of study (out of a total of 213,813 500 m cells in the Inuit-identified narwhal area).

3.4.3. *Comparison of western science-identified and Inuit-identified cetacean-populated areas overlapping with vessel noise*

Since Eclipse Sound was part of the Inuit-identified narwhal area and the 50% PVC, and had the highest average number of potential behavioural disturbance events (Fig. 4D), both the 50% PVC and the Inuit-identified narwhal area had similar vessel noise output profiles and the same maximum average number of potential underwater noise events. Both the 50% PVC and the Inuit-identified narwhal area results included Admiralty Inlet, which had a lower number of potential behavioural disturbance events. Furthermore, the Inuit-identified narwhal area was identified in the western portion of Parry Channel, while the narwhal 50% PVC was not identified in that area.

The Inuit-identified beluga and bowhead whale areas were identical, covering the same areas in western Parry Channel, so had identical overlays with underwater vessel noise outputs (Fig. 6C). Both had an average annual maximum 7.25 potential behavioural disturbance events per year within a single 500 m cell, similar to the beluga whale 50% PVC maximum value (Fig. 6A), albeit focused on a different area of the TI NMCA. The Inuit-identified beluga whale area was in the western section of Parry Channel near Resolute, while the beluga whale 50% PVC was on the eastern coast of Devon Island and in Maxwell Bay on southern Devon Island.

Next, the Inuit-identified cetacean-populated noise overlap areas and the 95% and 50% PVC noise overlap areas were compared to each other, for all vessel categories combined (Table 3). The narwhal 95% PVC overlaps were larger than all the Inuit-identified narwhal-populated overlaps, while beluga whale and bowhead whale Inuit-identified overlap areas were larger than the 95% PVC overlaps for every year, with one exception being beluga whale areas in 2015. (Table 3). Narwhal areas contained the largest areas of potential behavioural disturbance events with a maximum of ~60,00 km^2 in 2018 and a minimum in 2015 of ~32,300 km^2. The Inuit-identified beluga and bowhead whale areas with the largest area of potential behavioural disturbance events were ~28,100 km^2 in 2017 and a minimum of

~18,500 km^2 in 2015, which is smaller when compared to narwhal areas in the same years.

4. Discussion

4.1. Congruency between location of potential behavioural disturbance events and cetacean areas

Our results demonstrated that multiple vessels transited through the core use areas (50% PVCs) of narwhals and beluga whales within the TI NMCA over the period 2015–18, as well as through the Inuit-identified narwhal, beluga whale and bowhead whale areas. This could have led to multiple potential behavioural disturbance events (received sound level ≥ 120 dB), with some areas such as Eclipse Sound experiencing more disturbance events than others.

Vessel category and route were key factors in determining which cetacean utilisation distributions had the potential to be most impacted in TI NMCA. Cargo vessel, cruise ships, tankers and government vessels and icebreakers have higher noise source levels than the other 4 vessel categories (Table 1) and their signals travel farther, so these vessels produced a larger radius of noise which exceeded the behavioural disturbance threshold. For example, both beluga whales and narwhal areas had a high number of ships with high source levels transit through their 50% PVC core use areas, which led to a higher potential for behavioural disturbances.

Underwater noise originating from vessels has been reported to have high potential for negative impacts on cetaceans in the Arctic [25]. For instance, beluga whales have been observed to avoid icebreakers and alter their behaviour for days after an icebreaker disturbance [20], and avoid vessels in shallow estuaries [24]. Narwhals have been observed to temporarily stop all movement, and then flee from icebreakers [20], which jeopardises their communication for breeding and hunting, and subsequently introduces direct negative impacts on survival [56]. As described previously, the 120 dB threshold was chosen for this study because of the 2016 NOAA (National Oceanic Atmospheric Administration) Technical Guidance document that synthesised scientific literature to produce updated acoustic thresholds for cetaceans affected by anthropogenic noise [41]. However, fixed numerical thresholds themselves are not guaranteed representations of how cetaceans react in real life because there can be multiple factors that influence at which sound levels cetaceans' behaviours will be disturbed, including hearing sensitivity, the acoustic characteristic of the source, and the context of exposure [42]. For example, the presumed low frequency hearing range and known vocalisations of bowhead whales overlap significantly with ship noise and acoustic masking might occur at far distances, whereas the peak hearing range and vocalizations of beluga and narwhal are much higher and acoustic masking would mostly occur much closer to ships [21]. However, both beluga and narwhal have been shown to react to loud icebreaking ships at far distances with ice breaking noise just above ambient levels [20], suggesting that these species are quite sensitive to ship noise. In reality then, future research might conceptualise fuzzy thresholds centred at 120 dB to implicitly model the uncertainty present in behavioural responses to underwater noise.

The Inuit-identified cetacean-populated areas and PVC areas identified in this study differ in several locations, likely because of the methods used to collect the data. The Inuit-identified data originated from key knowledge holders in Resolute and Pond Inlet whose geographical region of expertise is focused near their community. Other communities within or adjacent to other parts of the TI NMCA (Grise Fiord, Arctic Bay, and Clyde River) were not included in this study due to lack of data, meaning that local knowledge of their wildlife areas was missed. Future inclusion of additional Inuit-identified wildlife areas, such as the Clyde River Knowledge Atlas [59], would therefore provide a more comprehensive data set.

In terms of potential issues with the western scientific knowledge of cetacean-populated areas, the PVCs were calculated from telemetry data from a small subset of each cetacean population. Tagging locations were biased to areas with logistical advantages that may have selected certain segments of the cetacean populations, so it is unclear whether the areas used by tagged cetaceans truly represent the population as a whole. For such reasons we mainly relied upon the 50% PVC for the cetacean distributions, as a compromise between uncertainty and current knowledge. For future work, additional telemetry data and additional community knowledge sources are required to robustly test which % PVC is best representative of wildlife core use areas, and whether these values vary with species. Inclusion of complementary data types and sources from multiple knowledge systems can therefore contribute to a more comprehensive understanding of where cetaceans are likely to be because each type of knowledge is gained through a different approach, so both contribute in their own unique ways [57].

The ship noise source levels used in this study were calculated from the ECHO Underwater Listening Station program in Vancouver, British Colombia. There is currently no published data available for the source levels of ships that travel through TI NMCA, so it is unknown as how well the Vancouver noise data represents real world conditions in the Arctic. Our study also used a single noise source level estimate for each vessel category, and did not account for variation between different vessels within the same category. This has the potential to bias the vessel noise outputs, because in reality vessels in the same category can have a range of source levels.

One additional limitation in our study is that we did not take into account the effect of slowdowns to 9 knots that have been implemented for bulk carrier vessels transiting to and from Mary River Iron Ore Mine in Milne Inlet [58,59]. Details about the source levels of vessels at specific speeds would be required to determine if the slowdown was sufficient to reduce the number of noise disturbance events within that area. Slowing down vessels will result in a reduced noise radius around the ship but will still likely cause noise disturbance [23]. Furthermore, other vessels such as cruise ships and tankers travelling through that region did not have slowdowns implemented and were recorded going up to 15.9 knots in 2017 [58].

4.2. Potential considerations for the management of TI NMCA

The congruency between areas of high ship noise and cetacean use indicates locations where cetaceans are likely to be disturbed by noise, and which may warrant heightened consideration when developing NMCA management plans for vessels transiting the TI. Speed reduction is a vessel management tool which generally leads to a reduction in noise source level [60] and received level noise (i.e. reducing speed reduces the radius around the ship that the 120 dB cetacean disturbance threshold is surpassed). Speed restrictions are more feasible as a noise management solution in the Arctic compared to completely closing an area, due to the geographical limitations and navigational hazards in the region which mean that safe alternate routes are not always available [19]. Studies show that variables such as ship size and ship speed can cause changes in noise levels [61,62]. In one study, regulations for vessel speed reduction averaged about a 10–15 dB decrease for large vessels transiting in Glacier Bay, Alaska [62]. It is uncertain to what degree vessel slowdown regulations would reduce the acoustic risk for cetaceans in TI NMCA, so future work is needed to determine the effects of slowdown mitigations on noise exposure.

Seasonal spatial vessel management tools to mitigate the impact of marine vessel traffic on cetaceans were identified by knowledge holders in all 14 communities that participated in the ACNV project [12]. Key, common recommendations included: avoid specific wildlife habitats; travel farther away from shorelines; restrict shipping during specific harvesting periods, migration periods, and sea ice freeze-up; conduct bathymetric surveys and chart existing and future corridors; and, create vessel slowdown areas. While the Inuit-identified recommendations are not yet legislated, documenting Inuit knowledge and perspectives was a crucial step in ensuring Inuit and northern voices are infused in the management and governance of the Arctic coast and waters.

Maintenance of hulls and propellers and the incorporation of new designs to decrease noise levels during vessel movement also reduces the potential impact of underwater vessel noise on cetaceans [63,64]. Currently there are no mandatory requirements for quiet ship designs, but the International Maritime Organization (IMO) guidelines for the reduction of underwater noise from commercial ships specifically address the impact of noise (reduction) on marine life [65]. Adoption of the IMO guidelines by vessels transiting TI NMCA would reduce underwater vessel noise.

Tallurutiup Imanga is the only available route for vessels transiting the eastern entrance of the Northwest Passage. It is also home to the only available migratory route for marine wildlife including marine mammals, birds, and fish [14]. In addition, TI is of critical importance to Inuit who exercise food sovereignty and their constitutionally-protected cultural practices while hunting and harvesting in the area, and whose food security is dependent upon the marine wildlife found in TI NMCA [9,14,66]. The findings of this study indicate that strategic, focused management considerations and mitigation strategies could reduce possible marine vessel-related disturbances to cetaceans in TI NMCA, particularly in areas where noise disturbance is likely. This can be supported through the implementation of existing, proven vessel management and noise reduction tools that mitigate marine vessel proximity to cetaceans, vessel noise outputs, and therefore cetacean disturbance [60]. Complementary use of multiple knowledge systems for decision-making and management considerations can enhance marine vessel noise and cetacean disturbance mitigation.

5. Conclusion

The highest potential behavioural disturbance events for narwhals occurred in Eclipse Sound and Milne Inlet, both in cetacean utilisation distribution areas (identified by western scientific knowledge) and in Inuit-identified cetacean-populated areas (identified by Inuit knowledge). Beluga and bowhead whale Inuit-identified areas had the highest potential behavioural disturbance events in western Parry Channel, while the most potential events in the utilisation distribution areas for beluga whales was off of the northeast coast of Devon Island (there was no utilisation distribution for bowhead whales in TI NMCA). The results from this study will inform decision-making related to ship traffic in the TI NMCA, and reiterates the importance of including both Inuit knowledge and western science. This comes at a time when the interim management plan for the area is being discussed and although the IIBA does not include any restrictions or rules for shipping in TI NMCA, several methods (such as improved hull and propellor designs [63]) can be implemented that could address this issue of ship-source noise exposure that could potentially impact cetaceans.

Given the complexity associated with shipping in the Canadian Arctic it is important to address potential issues with increases in vessel traffic before they cause harm in the future. This study helps to support decision- and policy-makers in their plans to manage vessels in TI NMCA, with a focus on the potential impacts of underwater noise from ships.

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CRediT authorship contribution statement

Zuzanna Kochanowicz: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing - review & editing, Visualization, Project administration. **Jackie Dawson:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition. **William Halliday:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Visualization. **Michael Sawada**: Conceptualization, Methodology, Writing - review & editing. **Luke Copland**: Conceptualization, Methodology, Writing - review & editing. **Natalie Carter:** Data curation, Writing - review & editing. **Adrian Nicoll:** Resources, Data curation. **Steven H. Ferguson:** Investigation, Resources, Data curation. **Mads Peter Heide-Jørgensen:** Investigation, Resources, Data curation. **Marianne Marcoux**: Investigation, Resources, Data curation. **Cortney Watt:** Investigation, Resources, Data curation. **David Yurkowski:** Investigation, Resources, Data curation.

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Declarations of interest

None.

Appendix

See Tables 4–7.

Table 4
Sound propagation loss values in decibels (log10) calculated in dBSea.

Location	Bulk Carrier	Cruise Ship	Government Vessel	Tug Boat
Baffin Bay	19.1	17.2	17.9	17.4
Parry Channel	19	17.5	18.2	17.5
Eclipse Sound - East	18.8	17.3	18.2	17.3
Eclipse Sound – Milne Inlet	19.8	18	18.8	18
Eclipse Sound – North	18.8	18.5	19.4	18.1
Admiralty Inlet	19	17.4	18.2	17.3
Nanisivik	20	20	20	19.7
Arctic Bay	20	20	20	19.7
Resolute Bay	17.6	17.3	18.2	16.9
Maxwell Bay	17.8	17.5	18.4	17.1
Croker Bay	19.6	19.3	20	18.8
Grise Fiord	19.1	17.5	18.2	17.4
Barrow Strait	18	16.9	17.6	16.8
Devon Island Bays	19.6	19.3	20	18.8
Admiralty Inlet Bays	20	20	20	19.7

Table 5
Details of the 500 m cells that exceeded 120 dB, in beluga whale and narwhal core use areas (50% PVC), with individual vessel categories from 2015 to 2018.

Vessel category	50% PVC overlap	Year	Maximum behavioural disturbance events	Cumulative total of cells in PVC	Area of behavioural disturbance events overlapping 50% PVC (Km^2)	Average area of behavioural disturbance events overlapping 50% PVC (Km^2)
Cargo	*Beluga whales*	2015	2	23,328	1603	2048
		2016	3		2189	
		2017	2		1987.5	
		2018	4		2411	
	Narwhals	2015	20	52,428	5540.5	5530
		2016	37		4929.5	
		2017	72		6017.75	
		2018	76		5632.5	
Cruise ship	*Beluga whales*	2015	5	23,328	2682.25	2479
		2016	1		1286.25	
		2017	2		2108	
		2018	9		3839.5	
	Narwhals	2015	7	52,428	3100.75	3544
		2016	5		3773.25	
		2017	5		2965.75	
		2018	14		4335.5	
Fishing	*Beluga whales*	2015	0	23,328	0	96
		2016	1		122.25	
		2017	2		136.75	
		2018	1		124.5	
	Narwhals	2015	1	52,428	827.5	800
		2016	1		341.25	
		2017	3		814.5	
		2018	2		1217	
Government	*Beluga whales*	2015	1	23,328	3407.5	2939
		2016	2		3396	
		2017	1		1919.5	
		2018	1		3032.75	
	Narwhals	2015	2	52,428	3461.25	5114
		2016	5		7688	
		2017	4		4827.5	
		2018	6		4477.25	
Military	*Beluga whales*	2015	0	23,328	0	0
		2016	0		0	
		2017	0		0	
		2018	0		0	
	Narwhals	2015	1	52,428	102.5	104
		2016	0		0	
		2017	3		313	
		2018	0		0	
Recreational	*Beluga whales*	2015	1	23,328	15.75	15
		2016	1		43.25	
		2017	0		0	
		2018	0		0	
	Narwhals	2015	1	52,428	188	897
		2016	3		621.25	
		2017	3		1147.25	
		2018	6		1631.75	
Tanker	*Beluga whales*	2015	1	23,328	1407.5	1480
		2016	1		1301	
		2017	1		1768.75	
		2018	1		1442.25	
	Narwhals	2015	4	52,428	3446.25	3452
		2016	5		3076	
		2017	4		3421	
		2018	7		3861.5	
Tug	*Beluga whales*	2015	0	23,328	0	0
		2016	0		0	
		2017	0		0	
		2018	0		0	
	Narwhals	2015	1	52,428	2173	1942
		2016	3		2205.5	
		2017	4		1733	
		2018	3		1657.75	

Table 6
Details of the 500 m cells that exceeded 120 dB, in beluga whale, narwhal and bowhead whale estimated species ranges (95% PVC), with individual vessel categories from 2015 to 2018.

Vessel category	50% PVC overlap	Year	Maximum behavioural disturbance events	Cumulative total of cells in PVC	Area of behavioural disturbance events overlapping 95% PVC (Km^2)	Average area of behavioural disturbance events overlapping 95% PVC (Km^2)
Cargo	*Beluga whales*	2015	2	134,701	4862.25	9881
		2016	3		6272.25	
		2017	4		12,057	
		2018	4		16,332	
	Narwhals	2015	20	307,562	23,835.25	28,997
		2016	37		20,766.75	
		2017	72		36,362.25	
		2018	76		35,025.25	
	Bowhead whales	2015	20	113,036	9066.75	11,893
		2016	37		9699	
		2017	72		15,063,25	
		2018	76		13,743.5	
Cruise ship	*Beluga whales*	2015	5	134,701	10,880.5	11,518
		2016	4		8045.5	
		2017	4		10,815.5	
		2018	12		16,332	
	Narwhals	2015	7	307,562	20,485.5	26,505
		2016	5		19,119	
		2017	5		23,976.5	
		2018	14		42,439.5	
	Bowhead whales	2015	6	113,036	6944.5	8877
		2016	4		7072.25	
		2017	5		7372.25	
		2018	14		14,119.75	
Fishing	*Beluga whales*	2015	1	134,701	138.25	574
		2016	1		632	
		2017	2		1012.75	
		2018	1		513.25	
	Narwhals	2015	1	307,562	1447.75	1844
		2016	1		1313.5	
		2017	3		2412.75	
		2018	2		2202.5	
	Bowhead whales	2015	1	113,036	429.25	545
		2016	1		406	
		2017	3		756.75	
		2018	2		587.5	
Government	*Beluga whales*	2015	1	134,701	7987.5	13,404
		2016	5		19,303.25	
		2017	3		11,948.5	
		2018	3		14,375.25	
	Narwhals	2015	3	307,562	21,953.25	28,978
		2016	5		35,426.5	
		2017	5		29,521	
		2018	6		29,012.5	
	Bowhead whales	2015	3	113,036	7382	12,430
		2016	4		13,222.5	
		2017	5		16,601.5	
		2018	6		12,514.25	
Military	*Beluga whales*	2015	2	134,701	282	81
		2016	0		0	
		2017	1		43.25	
		2018	0		0	
	Narwhals	2015	2	307,562	718.5	513
		2016	0		0	
		2017	3		1334.75	
		2018	0		0	
	Bowhead whales	2015	1	113,036	158.5	184
		2016	0		0	
		2017	3		577.25	
		2018	0		0	
Recreational	*Beluga whales*	2015	2	134,701	210.25	996
		2016	2		615	
		2017	4		1364.75	
		2018	5		1795.25	
	Narwhals	2015	2	307,562	622.25	3163
		2016	5		1891.25	
		2017	4		3962.75	
		2018	6		6176.5	
	Bowhead whales	2015	2	113,036	232.75	750.25
		2016	2		426.25	
		2017	2		714.75	
		2018	4		1627.25	

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Table 6 (*continued*)

Vessel category	50% PVC overlap	Year	Maximum behavioural disturbance events	Cumulative total of cells in PVC	Area of behavioural disturbance events overlapping 95% PVC (Km^2)	Average area of behavioural disturbance events overlapping 95% PVC (Km^2)
Tanker	*Beluga whales*	2015	2	134,701	6576.5	5660
		2016	2		5188.5	
		2017	1		5427.5	
		2018	3		5447.25	
	Narwhals	2015	4	307,562	15,913.75	15,543
		2016	5		13,581.5	
		2017	4		12,232	
		2018	7		20,446	
	Bowhead whales	2015	4	113,036	7072	6100
		2016	5		5758.5	
		2017	4		3004.75	
		2018	7		8564	
Tug	*Beluga whales*	2015	0	134,701	0	0
		2016	0		0	
		2017	0		0	
		2018	0		0	
	Narwhals	2015	1	307,562	2795.75	3790
		2016	3		3556.75	
		2017	4		6347.75	
		2018	3		2459.75	
	Bowhead whales	2015	1	113,036	498.25	1341
		2016	2		1187	
		2017	2		2981	
		2018	1		696.25	

Table 7
Details of the 500 m cells that exceeded 120 dB, in beluga whale, narwhal and bowhead whale Inuit-identified areas, with individual vessel categories from 2015 to 2018.

Vessel category	Inuit-identified cetacean overlap	Year	Maximum behavioural disturbance events	Cumulative total of cells in Inuit-identified cetacean areas	Area of behavioural disturbance events overlapping Inuit-identified cetacean area (Km^2)	Average area of behavioural disturbance events overlapping Inuit-identified cetacean area (Km^2)
Cargo	*Beluga whales*	2015	4	128,503	6479	9849
		2016	3		6309.75	
		2017	5		15,303	
		2018	3		11,305.75	
	Narwhals	2015	20	213,812	15,883.25	19,672
		2016	37		15,082.25	
		2017	72		25,862.50	
		2018	76		21,860	
	Bowhead whales	2015	4	128,503	6479	9849
		2016	3		6309.75	
		2017	5		15,303	
		2018	3		11,305.75	
Cruise ship	*Beluga whales*	2015	5	128,503	9392.25	11,656
		2016	4		10,894.25	
		2017	3		11,590	
		2018	8		14,749.25	
	Narwhals	2015	7	213,812	15,756.00	19,221
		2016	5		17,456.25	
		2017	5		18,290.75	
		2018	14		25,380.00	
	Bowhead whales	2015	5	128,503	9392.25	11,656
		2016	4		10,894.25	
		2017	3		11,590	
		2018	8		14,749.25	
Fishing	*Beluga whales*	2015	1	128,503	197.50	608
		2016	1		645.75	
		2017	1		1333	
		2018	1		256.50	
	Narwhals	2015	1	213,812	1176.75	1613
		2016	1		1181	
		2017	3		2350.50	
		2018	2		1744.75	
	Bowhead whales	2015	1	128,503	197.50	608
		2016	1		645.75	
		2017	1		1333	
		2018	1		256.50	
Government	*Beluga whales*	2015	3	128,503	4801.25	18,244
		2016	5		26,300.50	
		2017	5		21,623.50	
		2018	3		20,251	

(*continued on next page*)

Table 7 (*continued*)

Vessel category	Inuit-identified cetacean overlap	Year	Maximum behavioural disturbance events	Cumulative total of cells in Inuit-identified cetacean areas	Area of behavioural disturbance events overlapping Inuit-identified cetacean area (Km^2)	Average area of behavioural disturbance events overlapping Inuit-identified cetacean area (Km^2)
	Narwhals	2015	3	213,812	13,078.50	26,307
		2016	5		36,090	
			2017		5	
			29,015.50			
	2018		6	27,042.75		
	Bowhead whales	2015	3	128,503	4801.25	18,244
		2016	5		26,300.50	
		2017	5		21,623.50	
2018		3	20,251			
Military	*Beluga whales*	2015	2	128,503	589.75	190
		2016	0		0	
		2017	2		170	
		2018	0		0	
	Narwhals	2015	2	213,812	589.75	348
		2016	0		0	
		2017	3		803.75	
		2018	0		0	
	Bowhead whales	2015	2	128,503	589.75	190
		2016	0		0	
		2017	2		170	
		2018	0		0	
Recreational	*Beluga whales*	2015	2	128,503	397.50	966
		2016	2		738.75	
		2017	4		1126.25	
		2018	5		1603	
	Narwhals	2015	2	213,812	624.75	2170
		2016	3		1500.75	
		2017	4		2793.75	
		2018	6		3762	
	Bowhead whales	2015	2	128,503	397.50	966
		2016	2		738.75	
		2017	4		1126.25	
		2018	5		1603	
Tanker	*Beluga whales*	2015	2	128,503	8104.50	6456
		2016	2		5136.75	
		2017	1		5479.25	
		2018	3		7103.75	
	Narwhals	2015	4	213,812	12,982.50	12,045
		2016	5		10,868.75	
		2017	4		9939	
		2018	7		14,388.75	
	Bowhead whales	2015	2	128,503	8104.50	6456
		2016	2		5136.75	
		2017	1		5479.25	
		2018	3		7103.75	
Tug	*Beluga whales*	2015	0	128,503	0	362
		2016	1		1.75	
		2017	1		1257.75	
		2018	3		188.50	
	Narwhals	2015	1	213,812	2423.50	2747
		2016	3		2687.50	
		2017	4		3705.50	
		2018	3		2170.25	
	Bowhead whales	2015	0	128,503	0	362
		2016	1		1.75	
		2017	1		1257.75	
		2018	3		188.50	

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Glossary of terms

Automatic Identification System (AIS): automated tracking system fitted on ships to transmit their positions.

Behavioural disturbance event: a noise event that exceeds 120 decibels and risks causing a behavioural response from a marine mammal.

Behavioural response: a response from marine a mammal that is a change from its typical behaviour, such as altering vocalisation, moving from an important location and interruption of feeding.

Cetacean: whales, dolphins or porpoises; a marine mammal from the order *Cetacea*.

Frequency: the measurement of the number of times that a sound wave repeats itself per second.

Inuit Impact and Benefit Agreement (IIBA): a formal contract that is legally enforceable between an Inuit organization or community, and a corporate or government organization.

National Marine Conservation Area: representative marine areas that are established, protected, managed and conserved for the benefit, education and enjoyment of people.

Northwest Passage: a sea route through the Arctic Ocean (specifically through the Canadian Arctic Archipelago) that travels between the Atlantic and Pacific Oceans.

Octave bands: a frequency band where the highest frequency is twice as high as the lowest frequency.

Propagation loss: the decrease in sound intensity as a sound moves away from the sound source.

Polynya: an area of temporary or recurring open water surrounded by sea ice.

Raster: cells or pixels in the format of a grid (rows and columns) that each contain a value for information, such as a geographic location on the earth.

Telemetry: the gathering of information on marine animals' movements, using sensors or tags.

Underwater noise pollution: anthropogenic sources of noise from activities like shipping, sonar and seismic surveys.